The Last Kiloparsec

Milky Way Dust:
Impact on LSST photometry

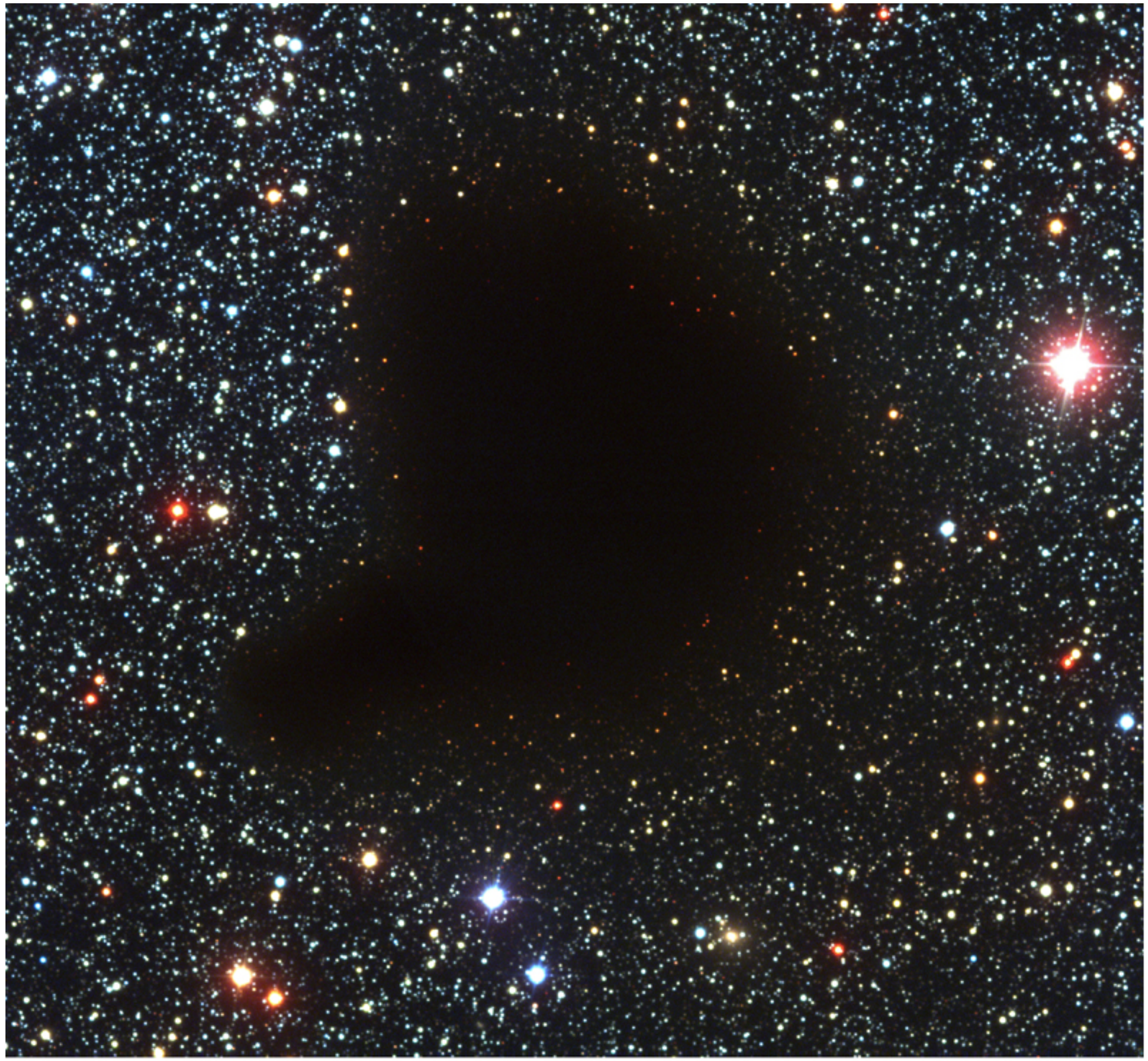
Douglas Finkbeiner
(including work by Gregory Green, Eddie Schlafly)

14 December, 2015
Last kpc workshop, UC Davis

Outline:

- What dust is
- What we know about variability in the reddening law
- How APOGEE has helped us find a new parameterization thereof
- How we make emission-based dust maps and estimate their systematics
- How we made the PS1 absorption based map and its issues
- How LSST can help make better dust maps
- How good those maps need to be for LSST science.

Dust clouds can be "dark clouds"



The "Black Cloud" B68
(VLT ANTU + FORS1)

ESO PR Photo 20a/99 (30 April 1999)

Or bright ("Reflection nebulae")

Rigel and the Witch Head Nebula
Image Credit & Copyright: Rogelio Bernal Andreo (Deep Sky Colors)

Or both. Often light reflects off the surface of dark clouds, while being absorbed by their cores:

Elephant's Trunk Nebula - IC1396A

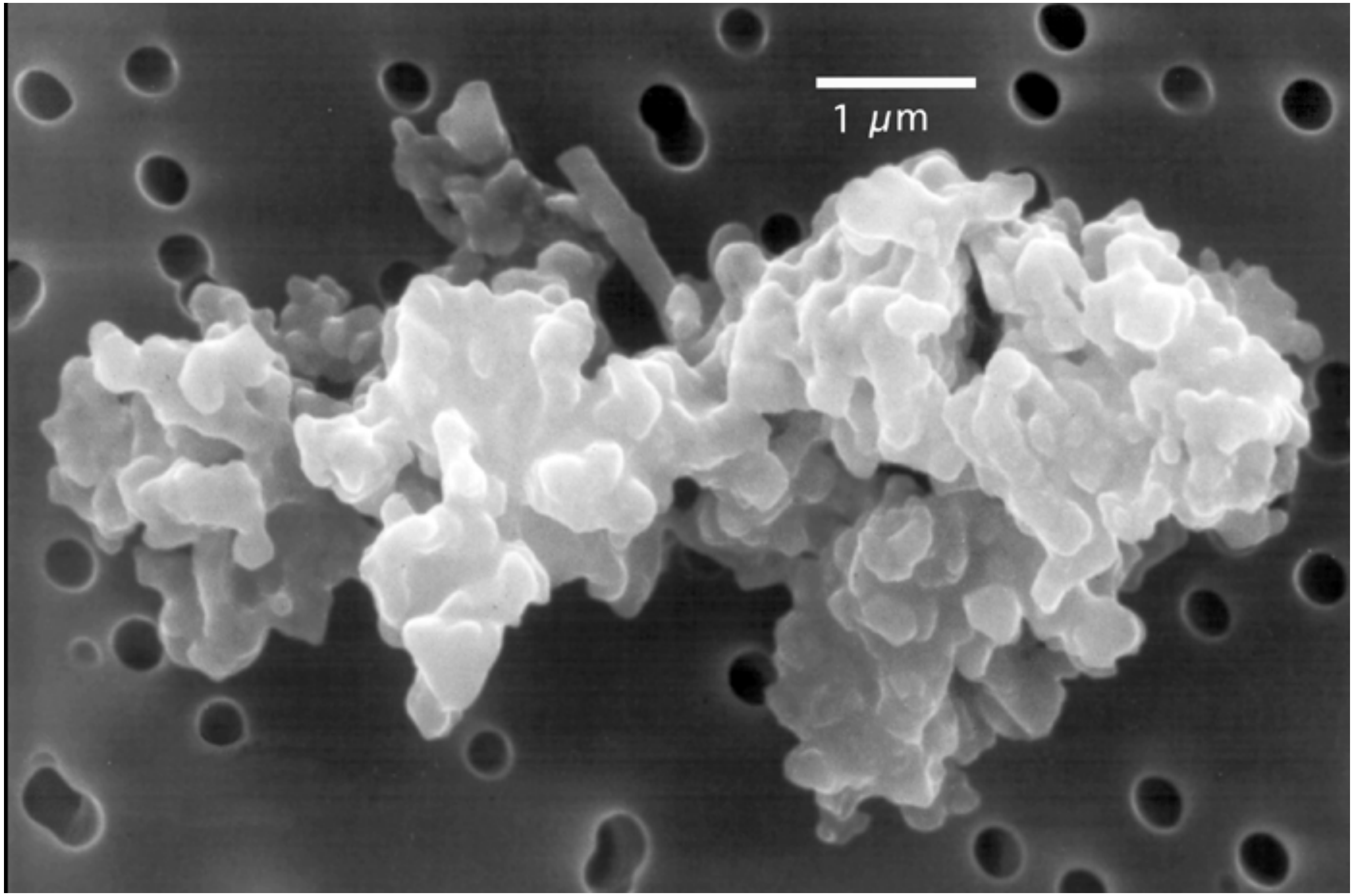
BY ANDREW HARRISON | PUBLISHED FEB 03 2011

The Elephant's Trunk nebula is a dark and dense globule of interstellar gas and dust in the star cluster IC 1396 – an ionised gas region located in the constellation Cepheus about 2,400 light years away from Earth.

Radiative transfer is a difficult problem to solve!

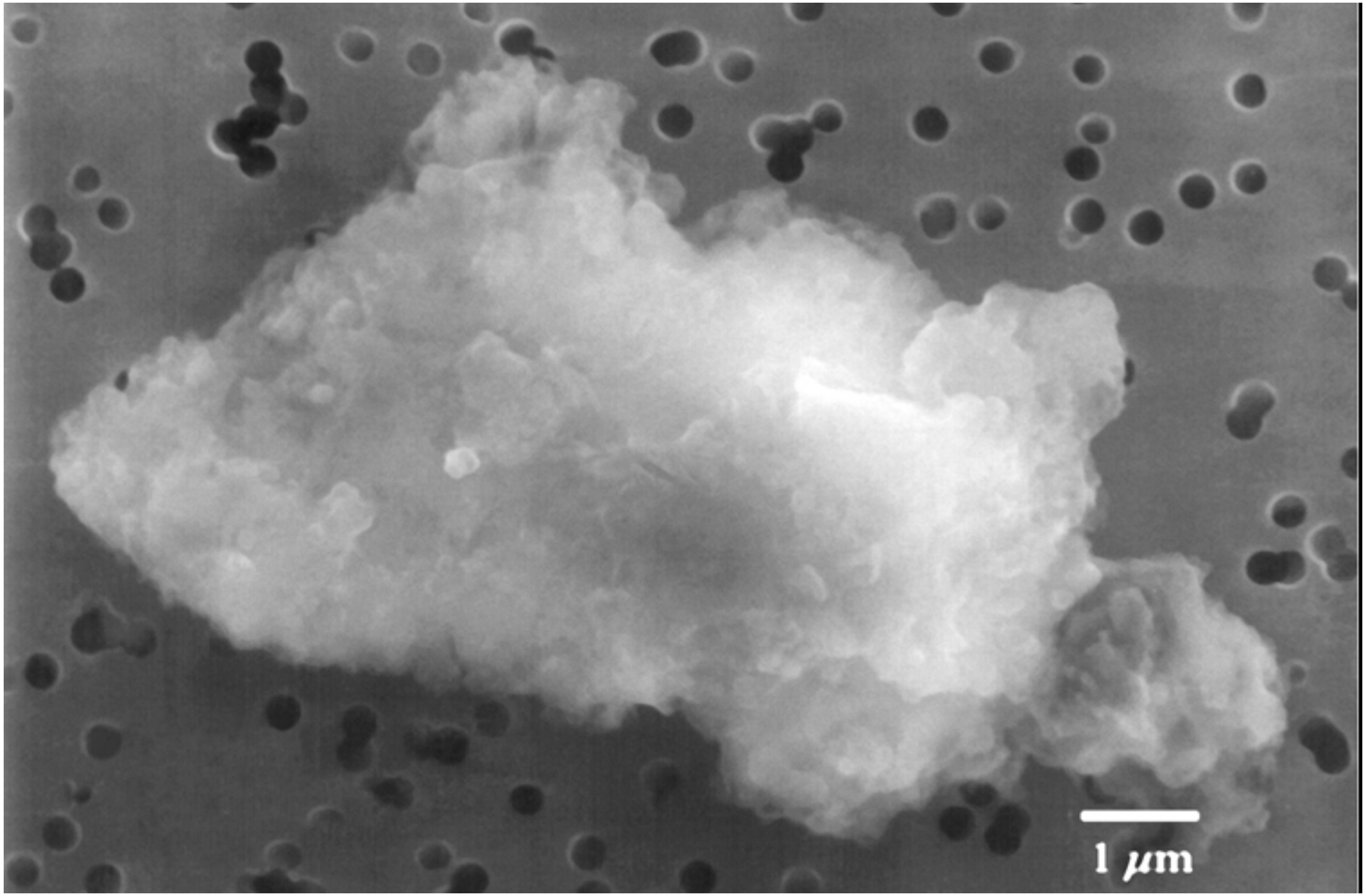
Fortunately (for LSST) we are trying to do cosmology in regions with relatively little dust along the line of sight. The dust is *optically thin,* and we are mostly concerned with the totally column density .

So, what is dust?



D. E. Brownlee, via Wikipedia

So, what is dust?



D. E. Brownlee, via Wikipedia

Those examples are interplanetary dust, highly processed pieces of comets and asteroids.

Interstellar dust grains are much smaller (< 1 micron). Such grains in the Solar System get dragged into the Sun on ~ 1 Myr timescales. (Poynting-Robertson)

The composition is uncertain

Jones et al. (1994) considered
- silicate
- carbonaceous
- SiC
- ices (e.g. water ice, ammonia ice, CO_2…)
- Fe
- …

Probably all of the above and more. But can we model with just a few things?

Sometimes nature is kind, and a simple approximation is sufficient…

D. Finkbeiner, Aka-jima, Japan

Sometimes nature is kind, and a simple approximation is sufficient…

Suppose that dust comes in two kinds: “silicate” and “carbonaceous.”

Draine & Lee (1984) provide the absorption efficiency and scattering efficiency (relative to classical spheres) of these as a function of wavelength and grain size.

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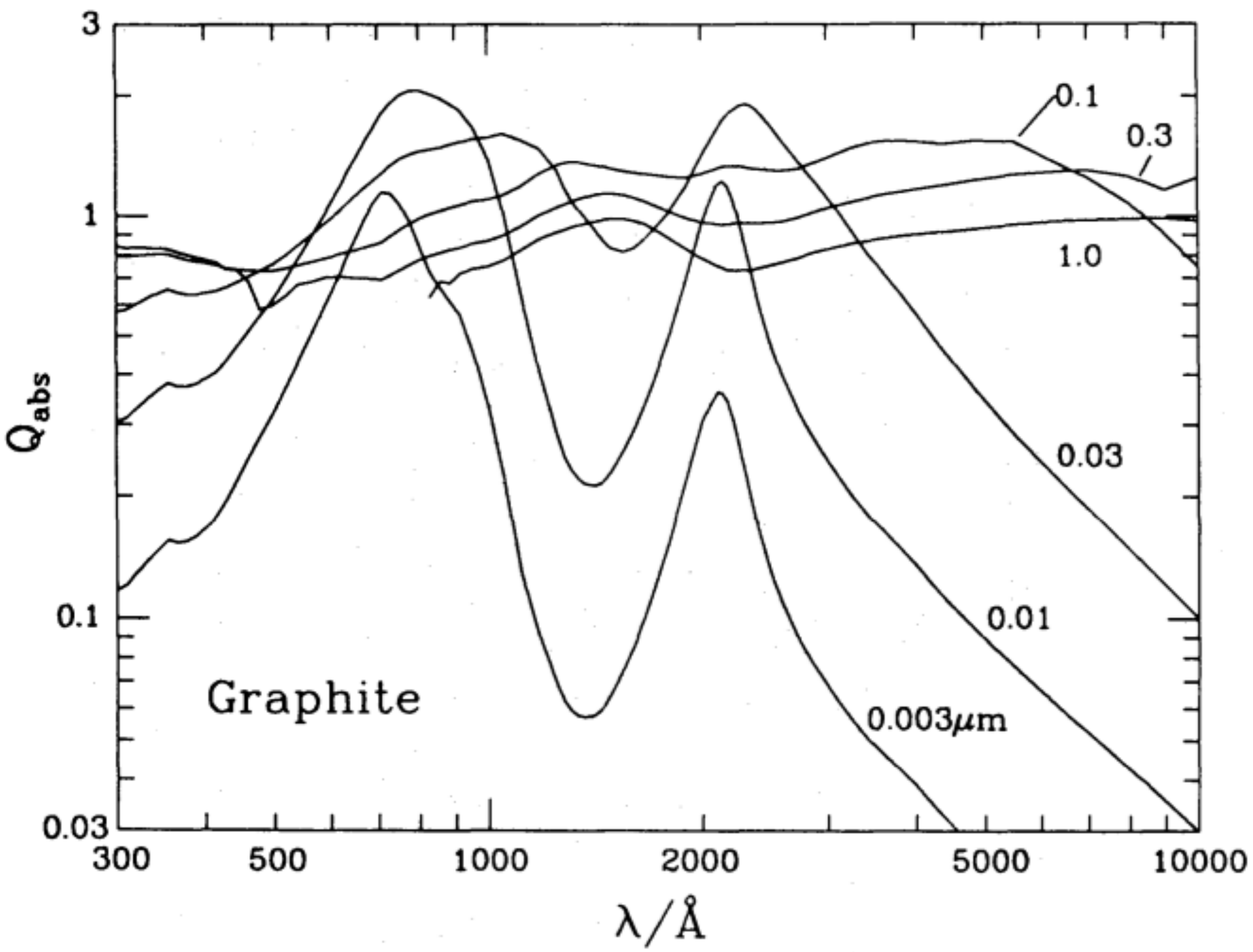


FIG. 4*a*

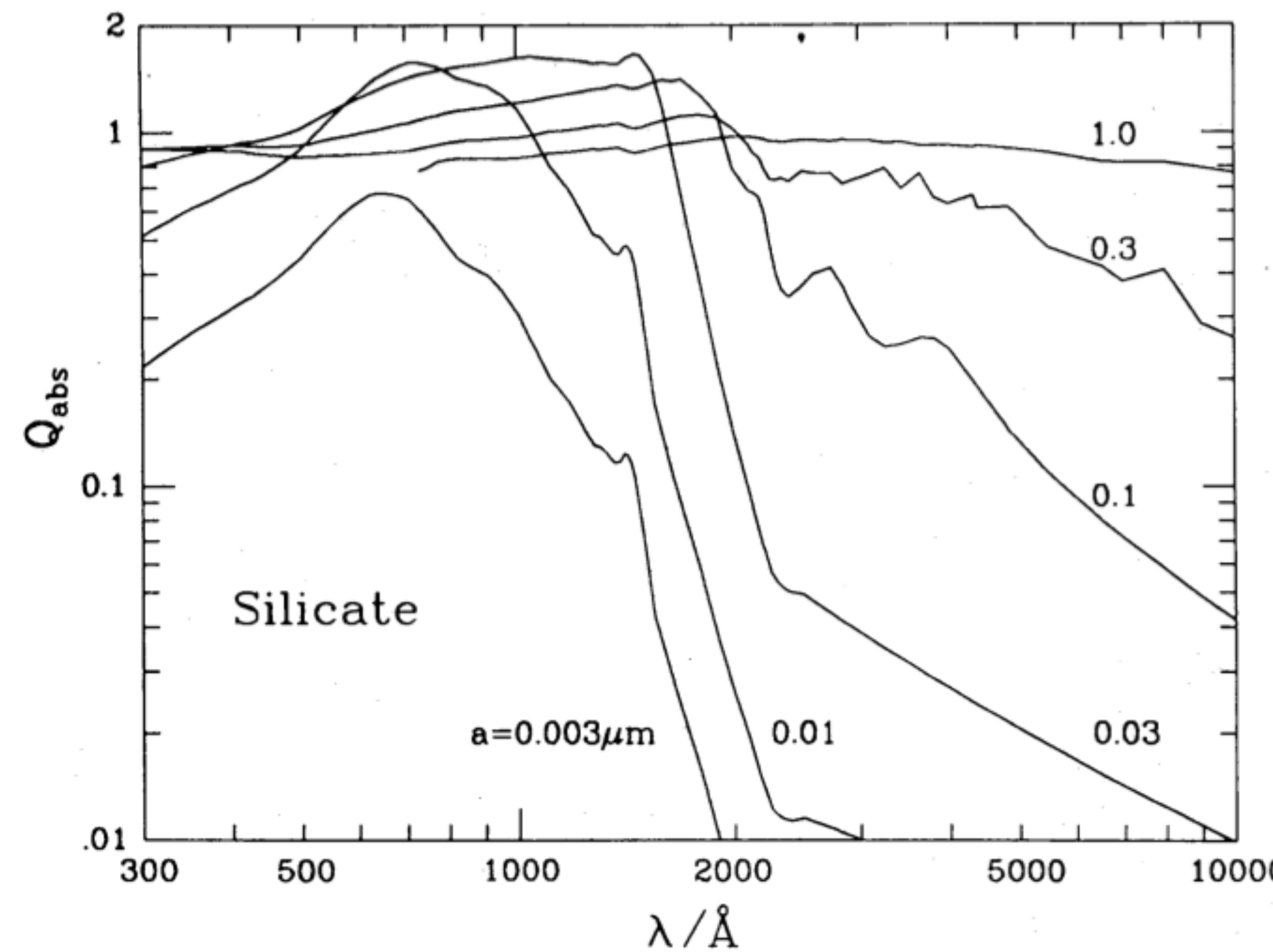


FIG. 5*a*

Draine & Lee (1984)

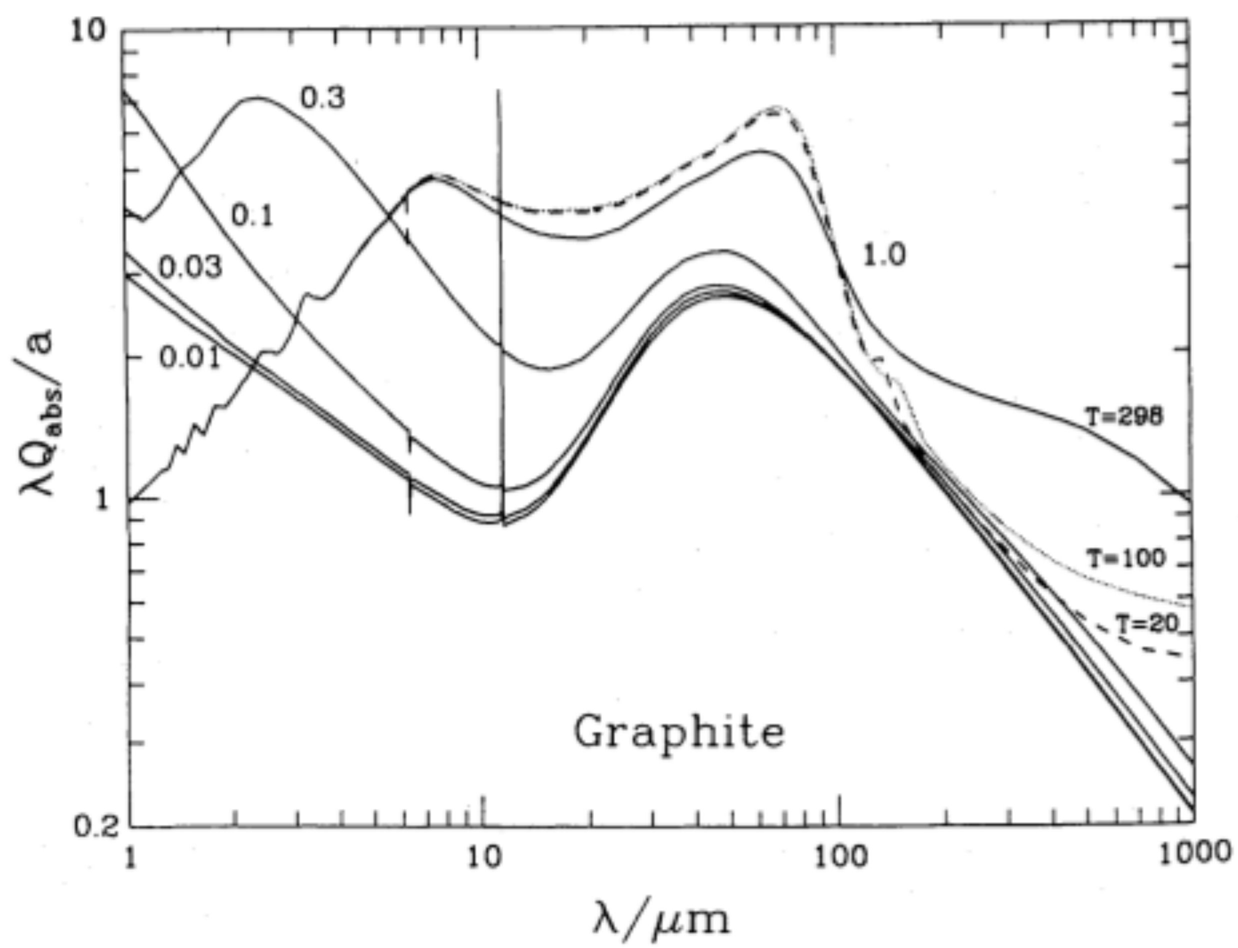


FIG. 4*b*

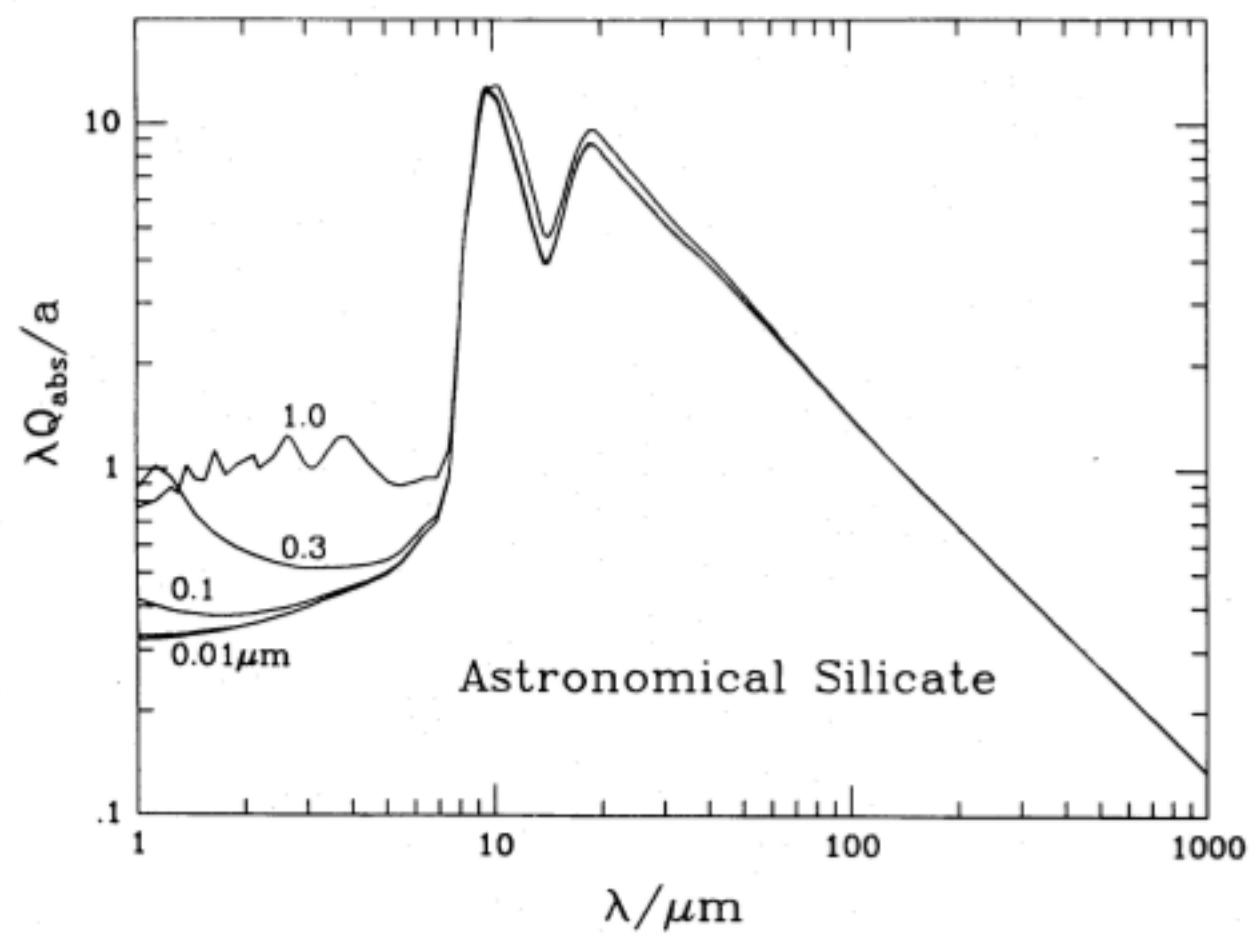
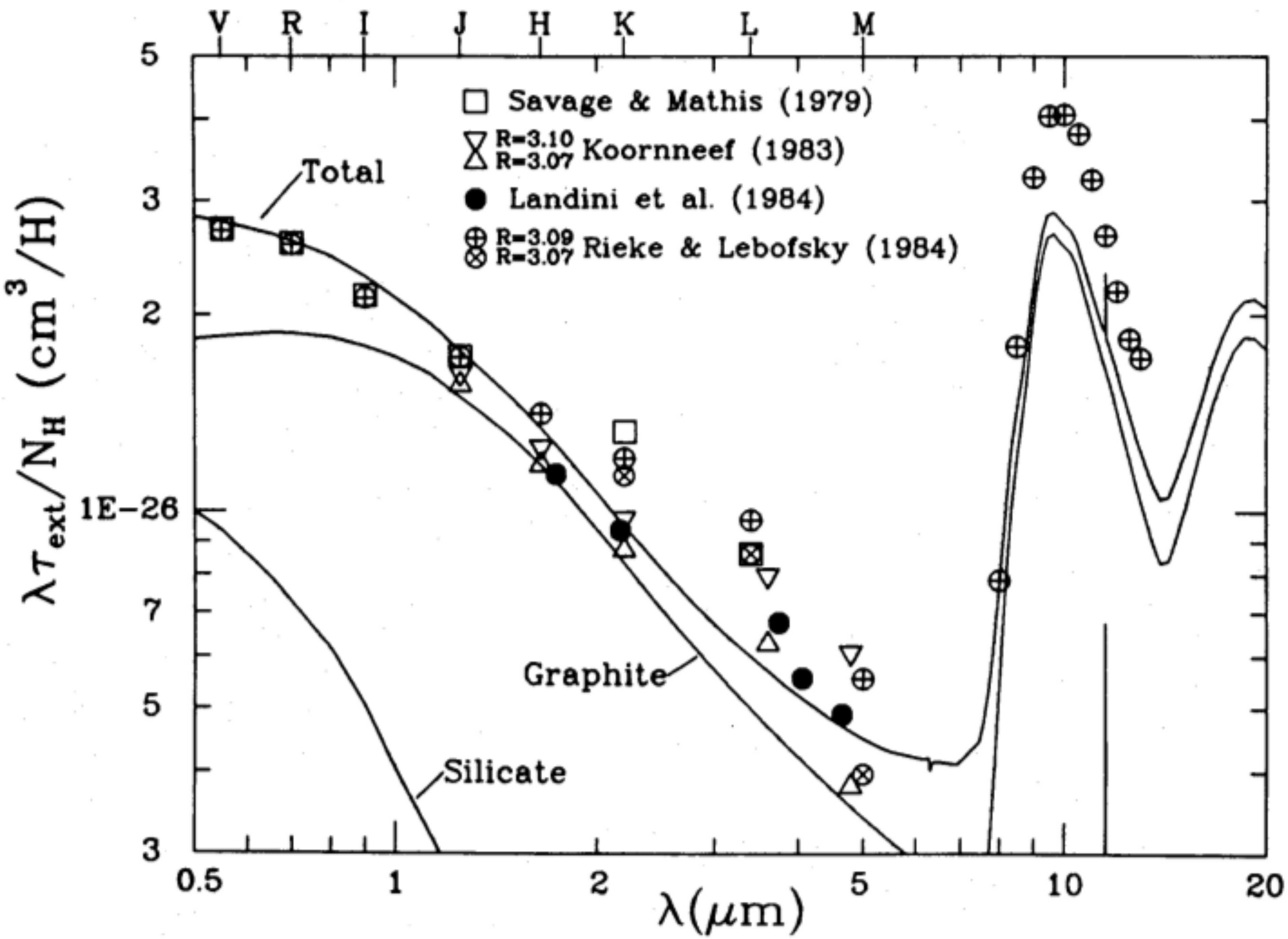


FIG. 5*b*

Draine & Lee (1984)



Draine & Lee (1984)

So we see that the wavelength dependence of absorption depends very much on the grain size and composition. And there is also the scattering term. (“Extinction” = absorption + scattering)

Weingartner & Draine (2001) parametrize the size distribution of “gra” and “sil” grains with > 15 parameters.

Argh!!

Is the situation hopeless???

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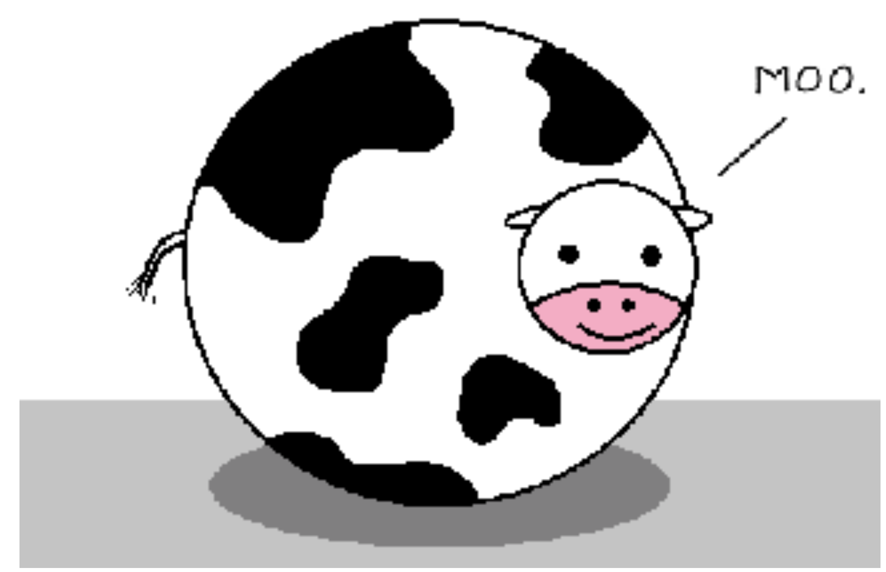
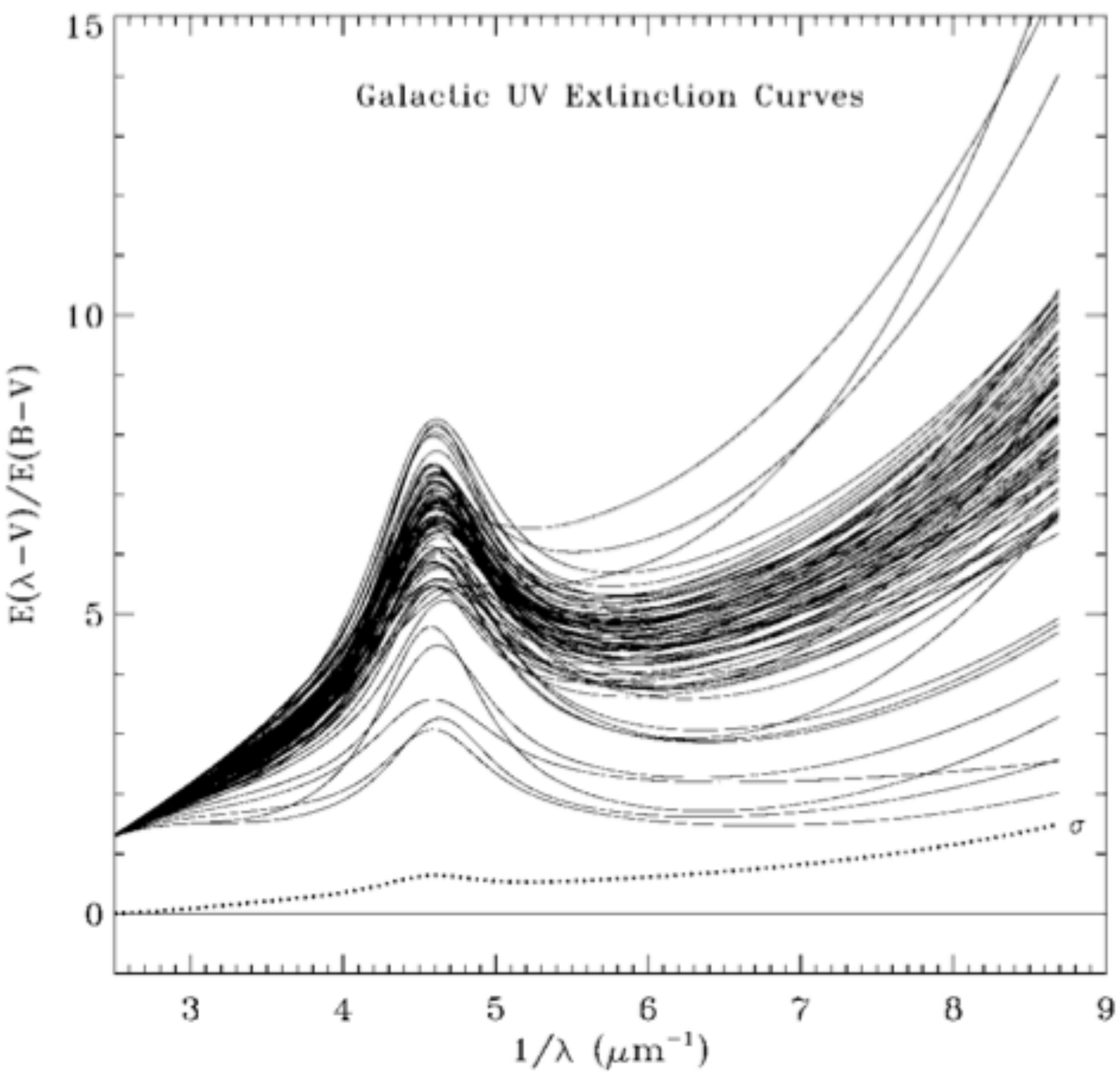
In practice, the ugrizy dependence of extinction appears to be a function of ~ 1 parameter.



Assume a spherical cow of uniform density.

In practice, the ugrizy dependence of extinction appears to be a function of ~ 1 parameter.



Fitzpatrick (1999)

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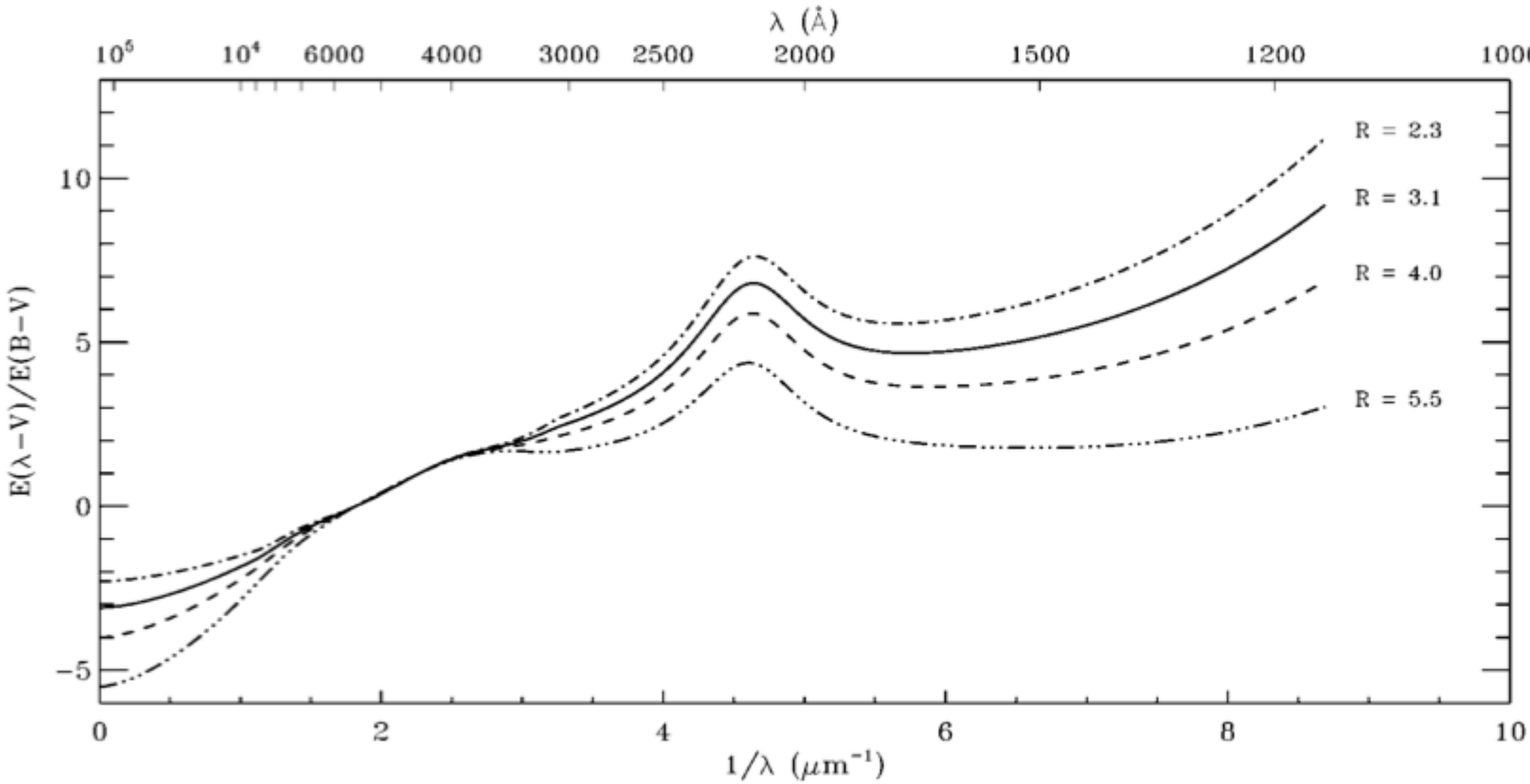

Fitzpatrick (1999)

In practice, the ugrizy dependence of extinction appears to be a function of ~ 1 parameter.

However, Fitzpatrick (1999) focuses on the UV end of the spectrum. Fitzpatrick & Massa (2009) consider the IR end, and come up with a different parameter, “alpha.”

There have been numerous parameterizations of the "extinction curve" (or "reddening law") and there is still some uncertainty.

This can matter. If one measures a reddening (say, g-r) and then wants to prediction extinction in every band, there is a strong lever arm.

So let's try to get this right.

THE OPTICAL-INFRARED EXTINCTION CURVE AND ITS VARIATION IN THE MILKY WAY

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G. M. Green,[2] K. W. Hodapp,[4] N. Kaiser,[4] E. A. Magnier,[4] N. F. Martin,[6,1] R. J. Wainscoat,[4]

Draft version November 9, 2015

ABSTRACT

The dust extinction curve is a critical component of many observational programs and an important diagnostic of the physics of the interstellar medium. Here we present new measurements of the dust extinction curve and its variation towards tens of thousands of stars, a hundred-fold larger sample than in existing detailed studies. We use data from the APOGEE spectroscopic survey in combination with ten-band photometry from Pan-STARRS1, 2MASS, and WISE. We find that the extinction curve in the optical through infrared is well characterized by a one-parameter family of curves described by $R(V)$, with little need for further parameters. We find that the extinction curve is more uniform than suggested in past works, with $\sigma(R(V)) = 0.2$, and with less than two percent of sight lines having $R(V) > 4$. Our data show new, large, spatially coherent structures in $R(V)$ throughout the Galactic plane. The $R(V)$ variations are on scales much larger than individual molecular clouds, indicating that grain growth in dense molecular cloud environments is not the primary driver of $R(V)$ variations. Indeed, we find no correlation between $R(V)$ and dust column density up to $E(B-V) \approx 2$. Finally, we discover a strong relationship between $R(V)$ and the far-infrared dust spectral energy distribution.

Subject headings: ISM: dust, extinction — ISM: structure — ISM: clouds

Idea:

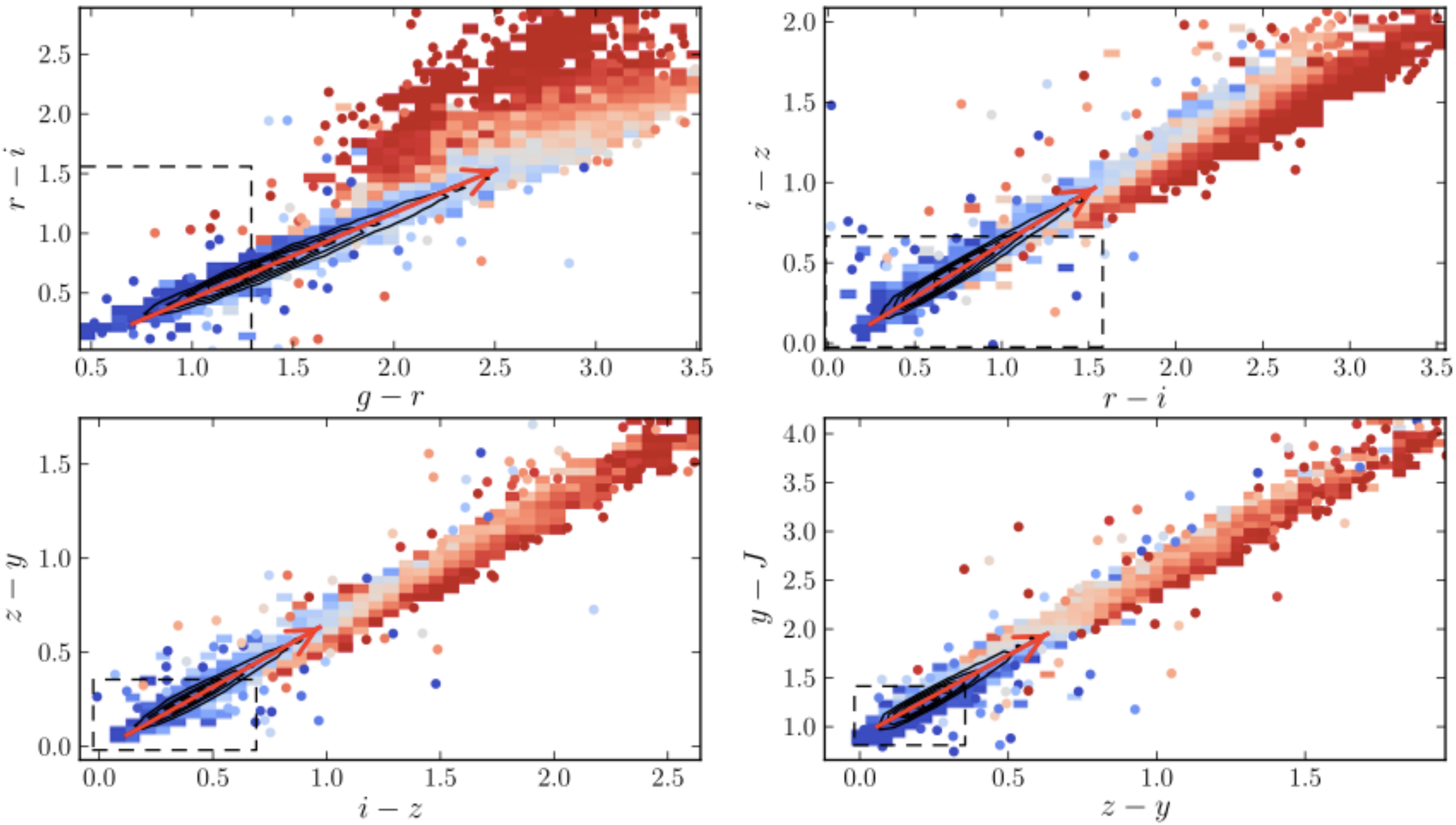
- Use APOGEE spectra for 40,000 stars to get type, metallicity, etc. from lines only.

- Estimate intrinsic color of star.

- Compare to measured color in 10 bands. Color shift is reddening.

- Use principal component analysis (PCA) to examine variation around mean reddening law.

- Compare to predictions of Fitzpatrick and others.



Schlafly + (2015)
Color indicates T_star

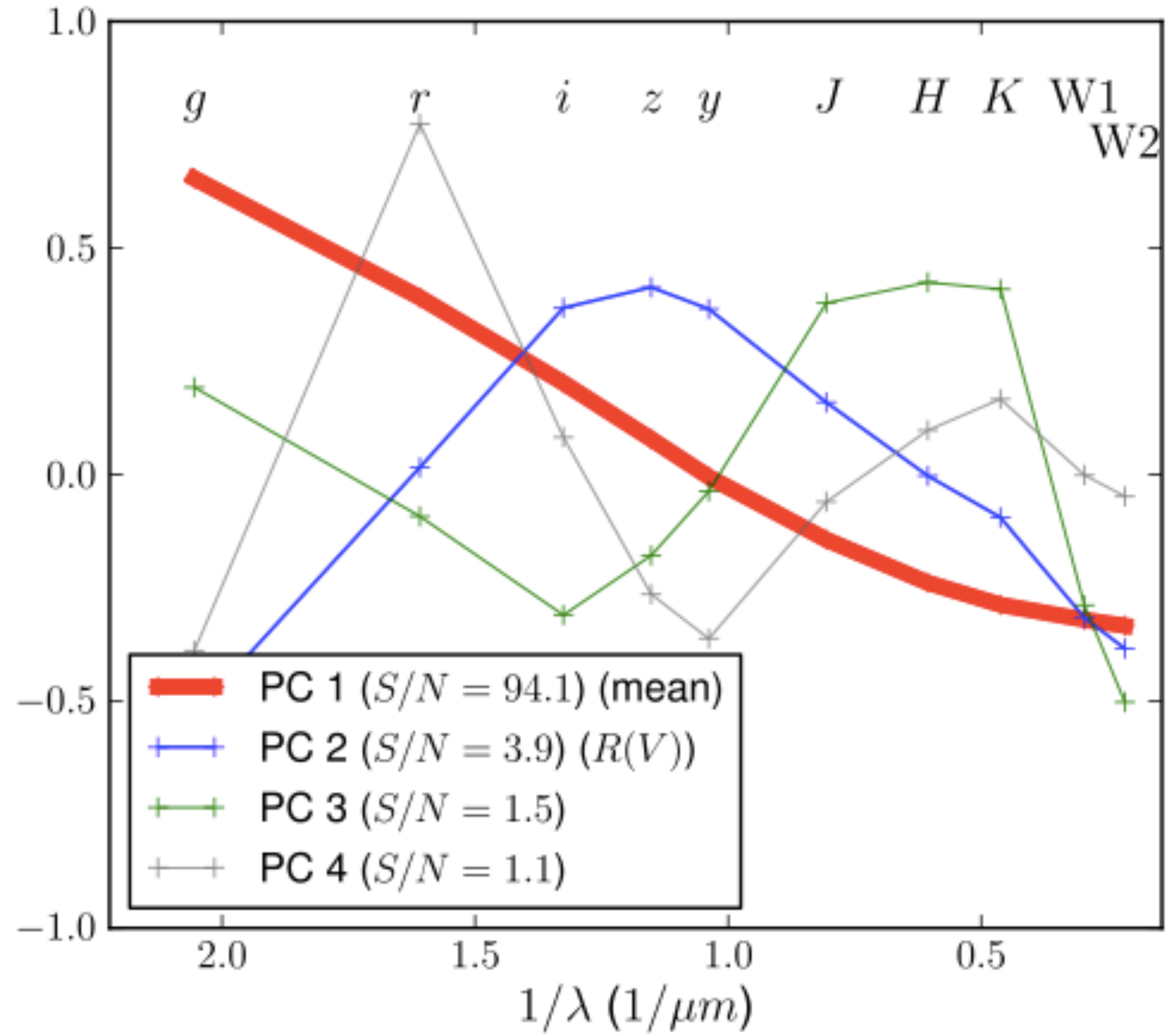
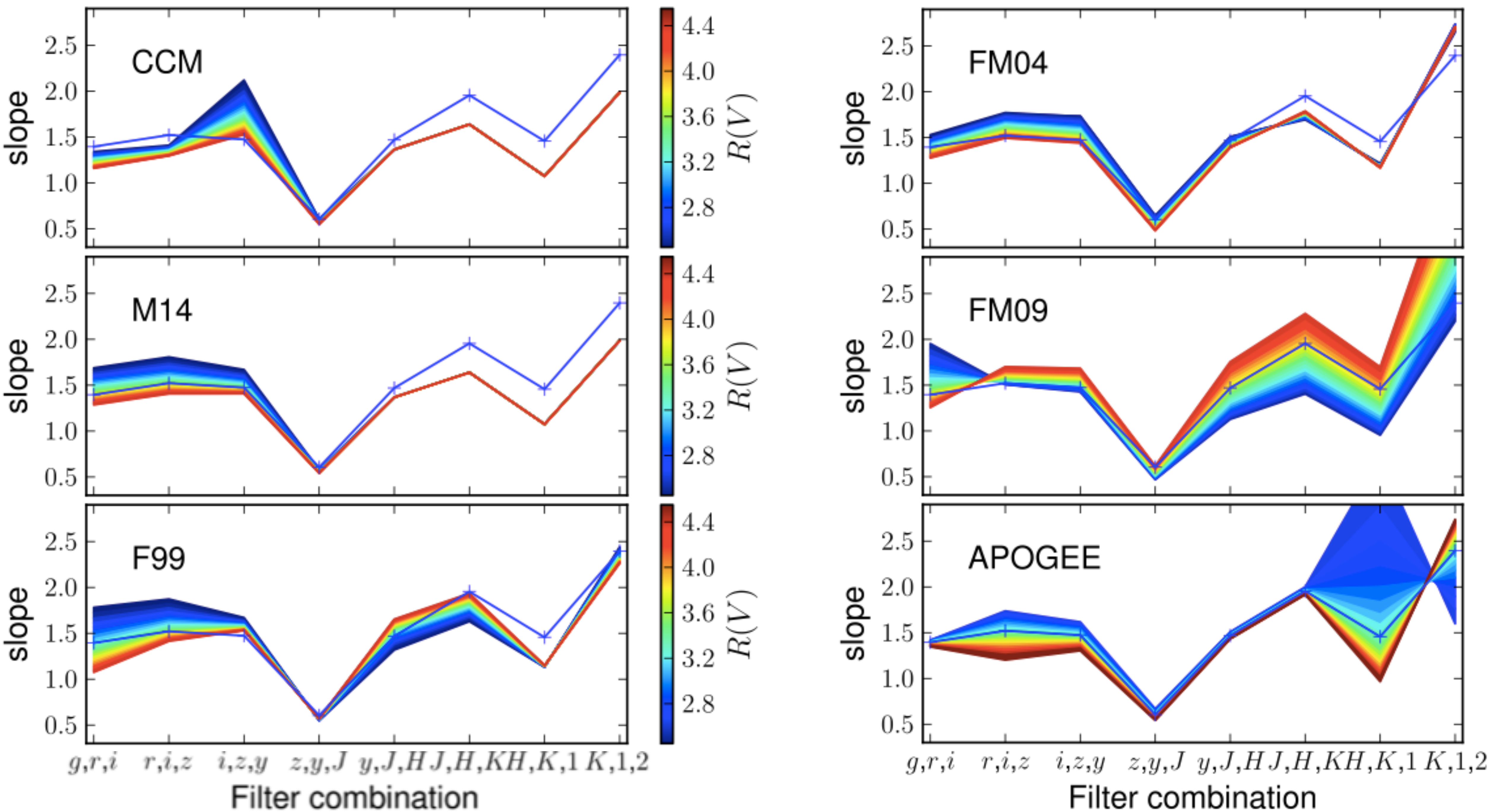


FIG. 7.— The first 4 principal components of the extinction curve (ignoring gray). The legend gives the typical signal-to-noise at which variations in each principal component can be measured, and the top labels indicate the filter corresponding to each point. The first principal component is essentially the mean reddening vector. The second principal component is very similar to the effect of $R(V)$ in other formulations of the extinction curve; increasing $R(V)$ reduces the curvature of the extinction curve. The later principal components can only be measured with $S/N \approx 1$ in this data: they are essentially not necessary to describe the observed spectrum of a single star, though formally over the whole APOGEE sample they are statistically significant.

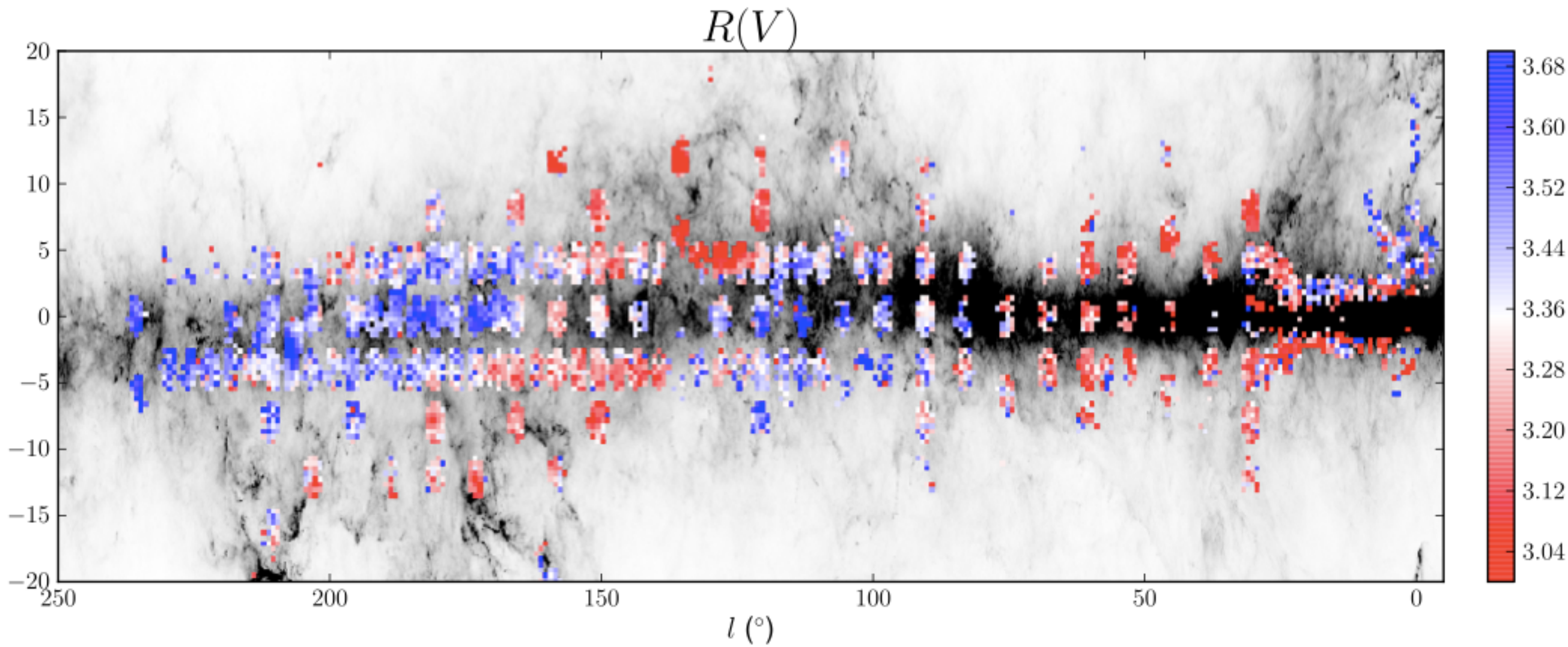


Schlafly + (2015)

See Eddie's poster for more details…

Spatial variation of the reddening law

(Here "R(V)" is the Schlafly et al. proxy for R(V))



Spatial distribution of dust.

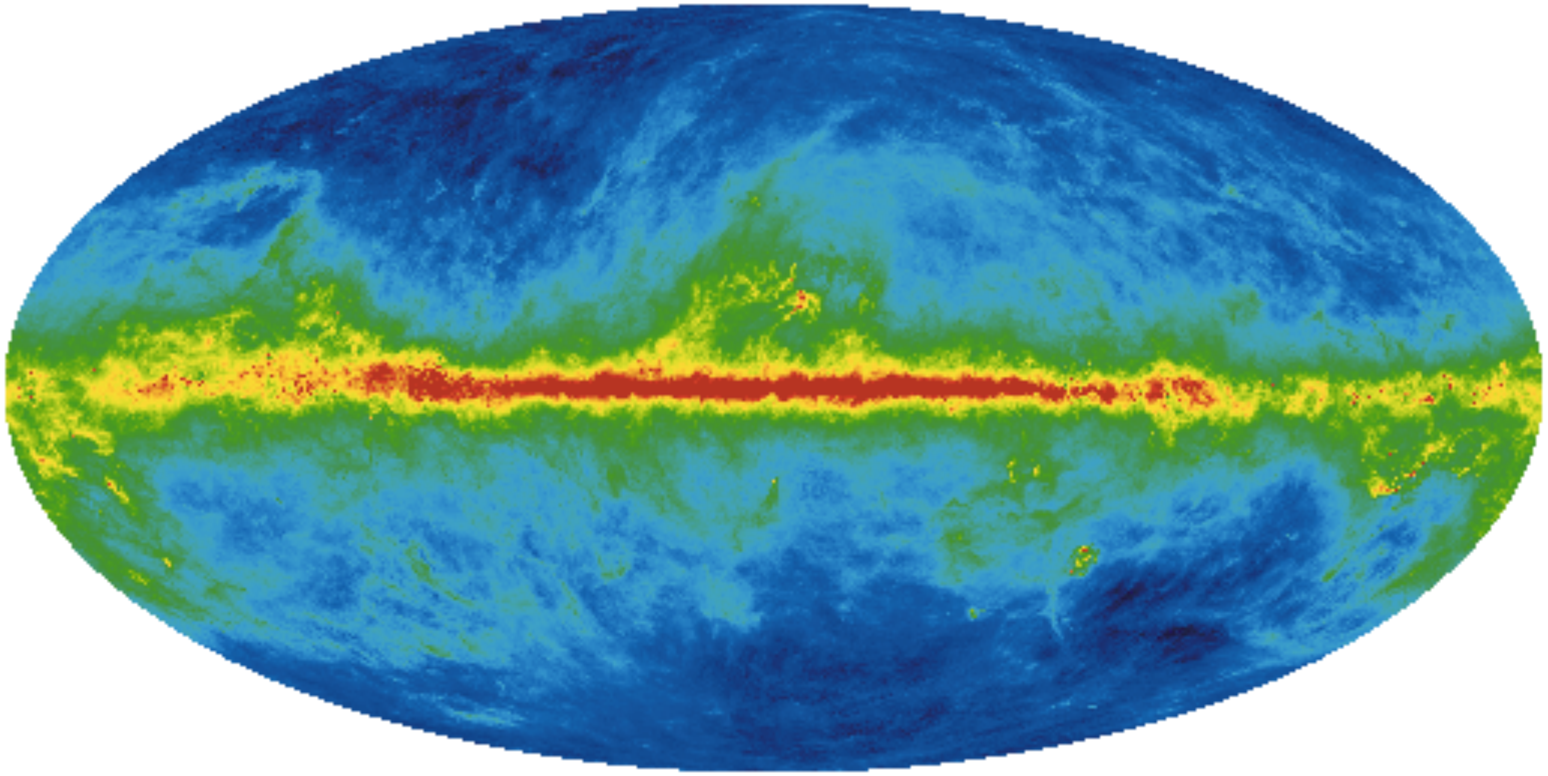
The distribution of dust is mapped via its emission
(IRAS, DIRBE, Planck)

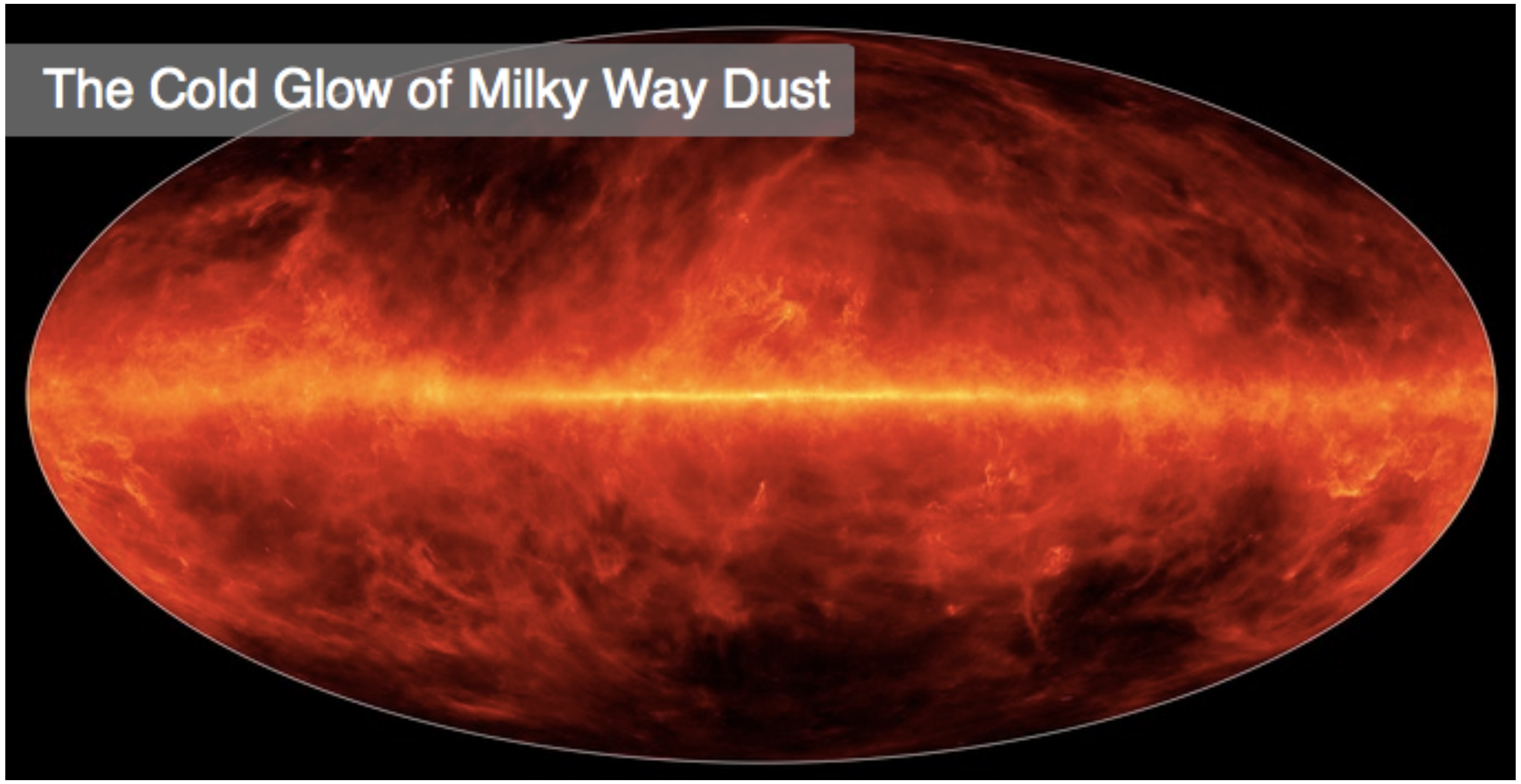
or emission of correlated material
(HI, CO, etc., e.g. Burstein-Heiles)

or by starlight reddening:
NICE, NICER (2MASS) … Green+ (2015) (2MASS+Pan-STARRS1)

Spatial distribution of dust

Schlegel, Finkbeiner, & Davis (1998; SFD) and *Planck*





Spatial distribution of dust: pros/cons

The distribution of dust is mapped via its emission
(IRAS, DIRBE, Planck)
Pro: sensitive, fixed spatial resolution,
Con: zodiacal light, leakage of LSS signal (especially in Planck)

or emission of correlated material
(HI, CO, etc., e.g. Burstein-Heiles)
Pro: no zodi, no LSS, *you know the zero point*
Con: Not actually dust. Dust/gas ratio varies. Worse angular resolution.

or by starlight reddening:
Pro: measures what you want to know! No zodi, no LSS, etc. Can do 3D
Con: Need background stars (variable depth, resolution), stellar models may be wrong.

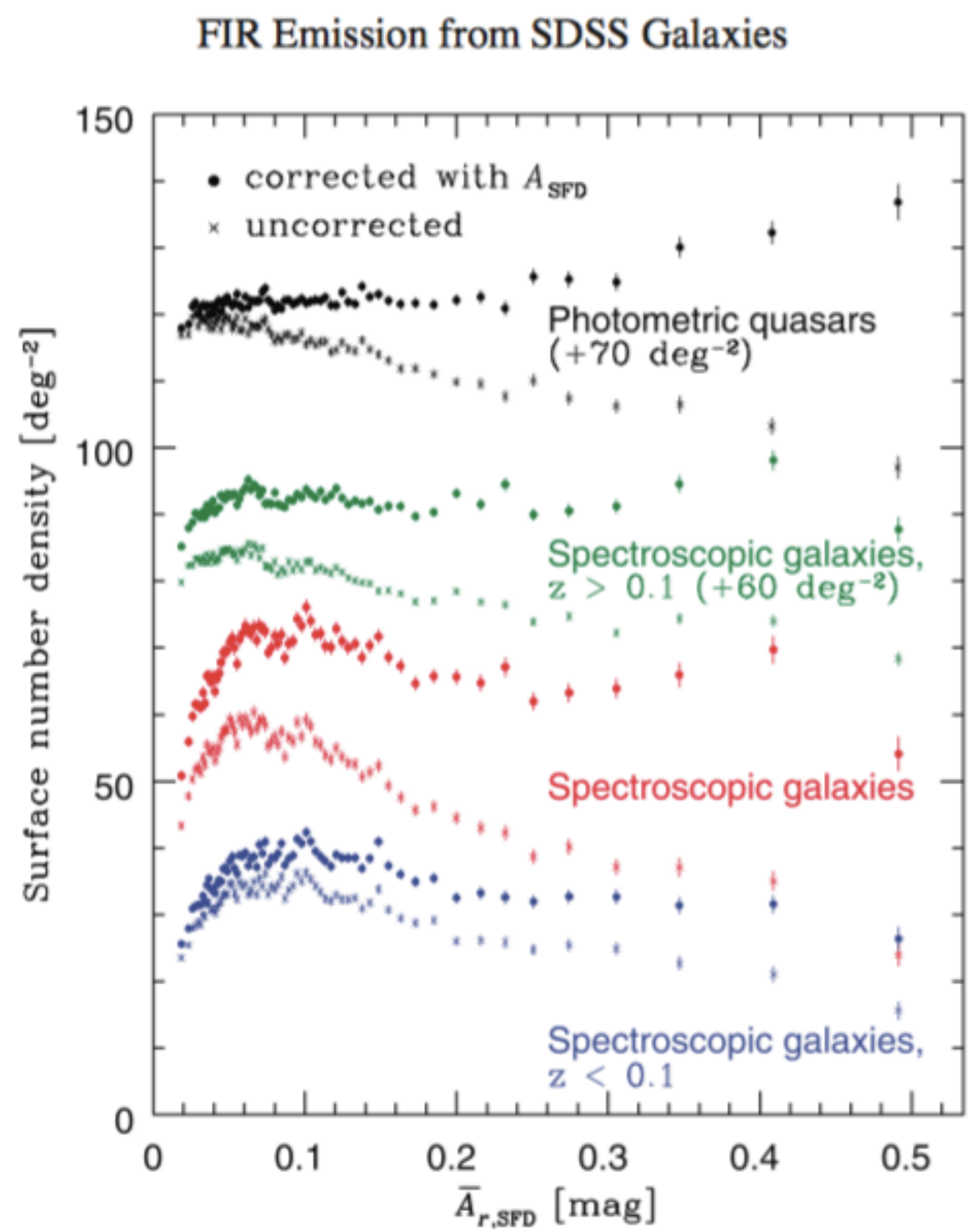
How to make a dust map (based on emission)

- Measure far IR emission at many wavelengths
- Subtract zodiacal light from interplanetary dust
- Subtract mean Cosmic IR Backround (CIB)
- Fit a naive model of emission vs. Tdust and column density
- Calibrate it to reddening using galaxies or stars.

Large-scale systematics may be dominated by zodiacal light.
Smaller-scale structure dominated by CIB anisotropy (LSS).

The “Yahata Plot” (K. Yahata+, 2007)

If noise (Poisson or otherwise) scatters points in both x and y, spurious behavior is seen in number counts vs. dust plots:



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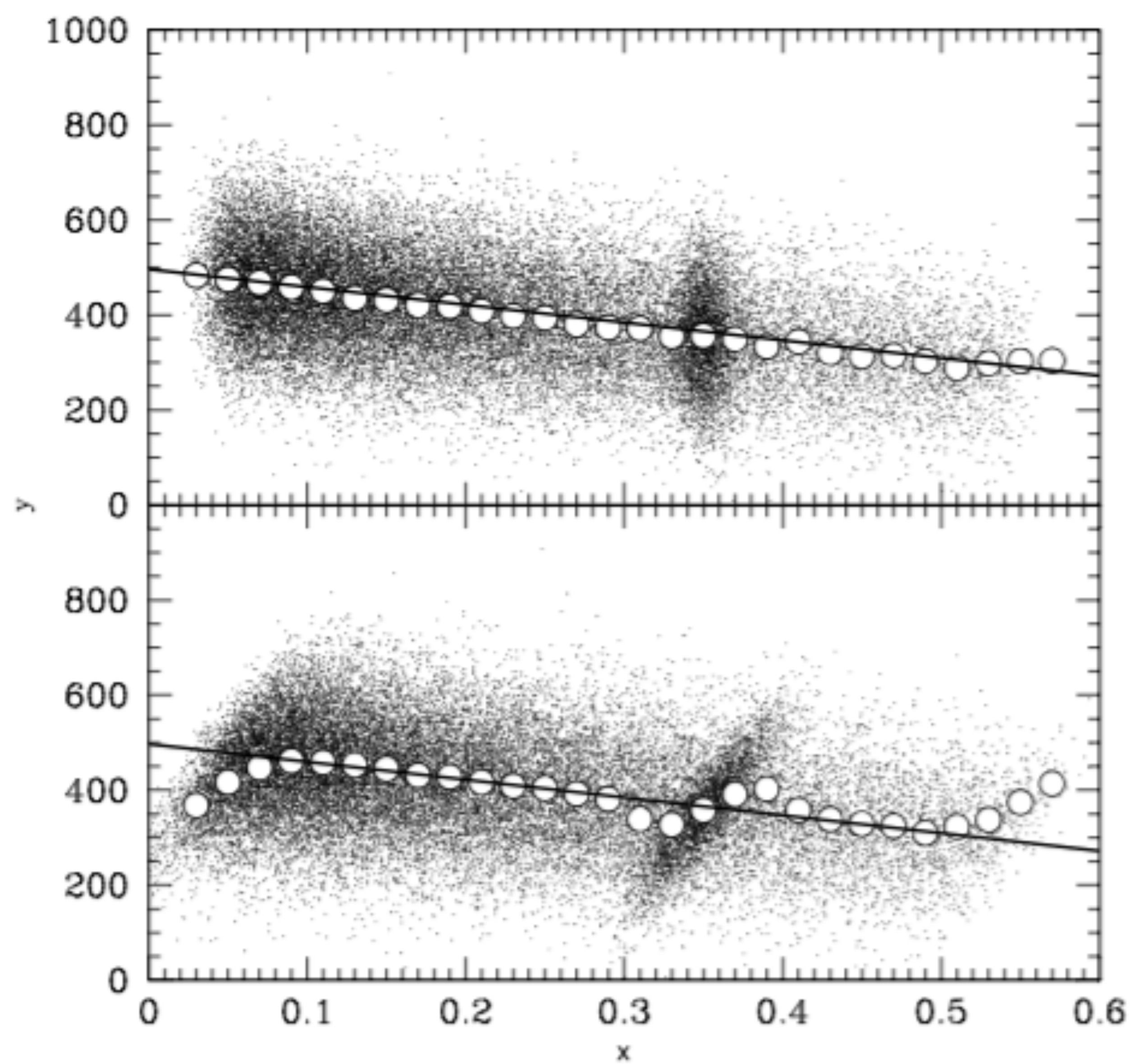
K. Yahata et al.



The "Yahata Plot" (K. Yahata+, 2007)

Josh Peek has stacked Spitzer data for the galaxies that might be responsible for the FIR emission, and finds it is not nearly bright enough.

This is still a mystery…

Therefore, it would be safer to have an alternative dust map that is not contaminated by large-scale structure to begin with!

3-D dust with Pan-STARRS

Use g,r,i,z,y photometry of 800,000,000 stars plus 2MASS where available.

- Distance to specific dust clouds
- Combine with HI, CO maps to identify distances to velocity components
- 3-D stellar map
- "Virgo overdensity," tidal streams, dwarf galaxies...
- Prelude to GAIA

3-D dust with Pan-STARRS

Greg Green

Bayesian pundit,
MCMC connoisseur

Eddie Schlafly

Calibrator in chief

Mario Jurić

Database guru

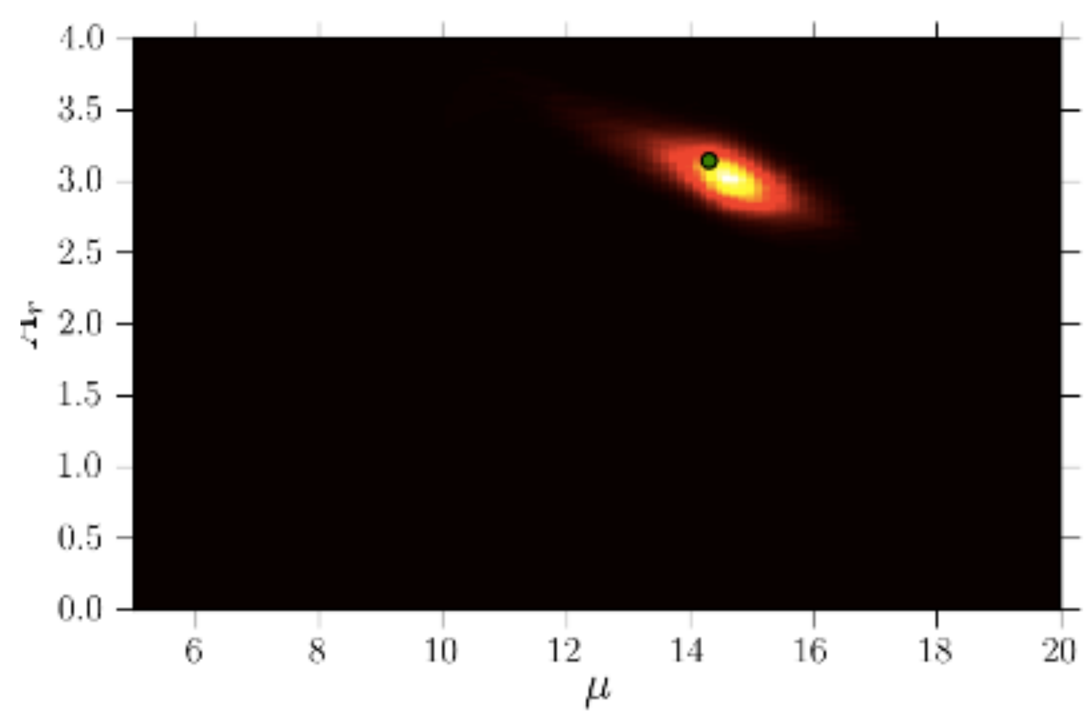
3-D dust with Pan-STARRS

- Pan-STARRS has collected photometry on $\sim 5 \times 10^8$ stars.
- Group stars into sufficiently small pixels.
- Calculate photometric parallax and reddening for each star.
- Find reddening profile as a function of distance which is consistent with all stars in pixel.

3-D dust with Pan-STARRS

For each star our goal is to compare a stellar template library with observed apparent stellar magnitudes in order to determine the joint posterior $p(\mu, A_r \,|\, \vec{m}_{\rm obs})$. Here,

$$\mu = \text{Distance Modulus}\,,$$
$$A_r = \text{Extinction in } r \text{ band}\,,$$
$$\vec{m}_{\rm obs} = \text{Observed } grizy \text{ apparent magnitudes}\,.$$



3-D dust with Pan-STARRS

Two intrinsic parameters used to describe star:

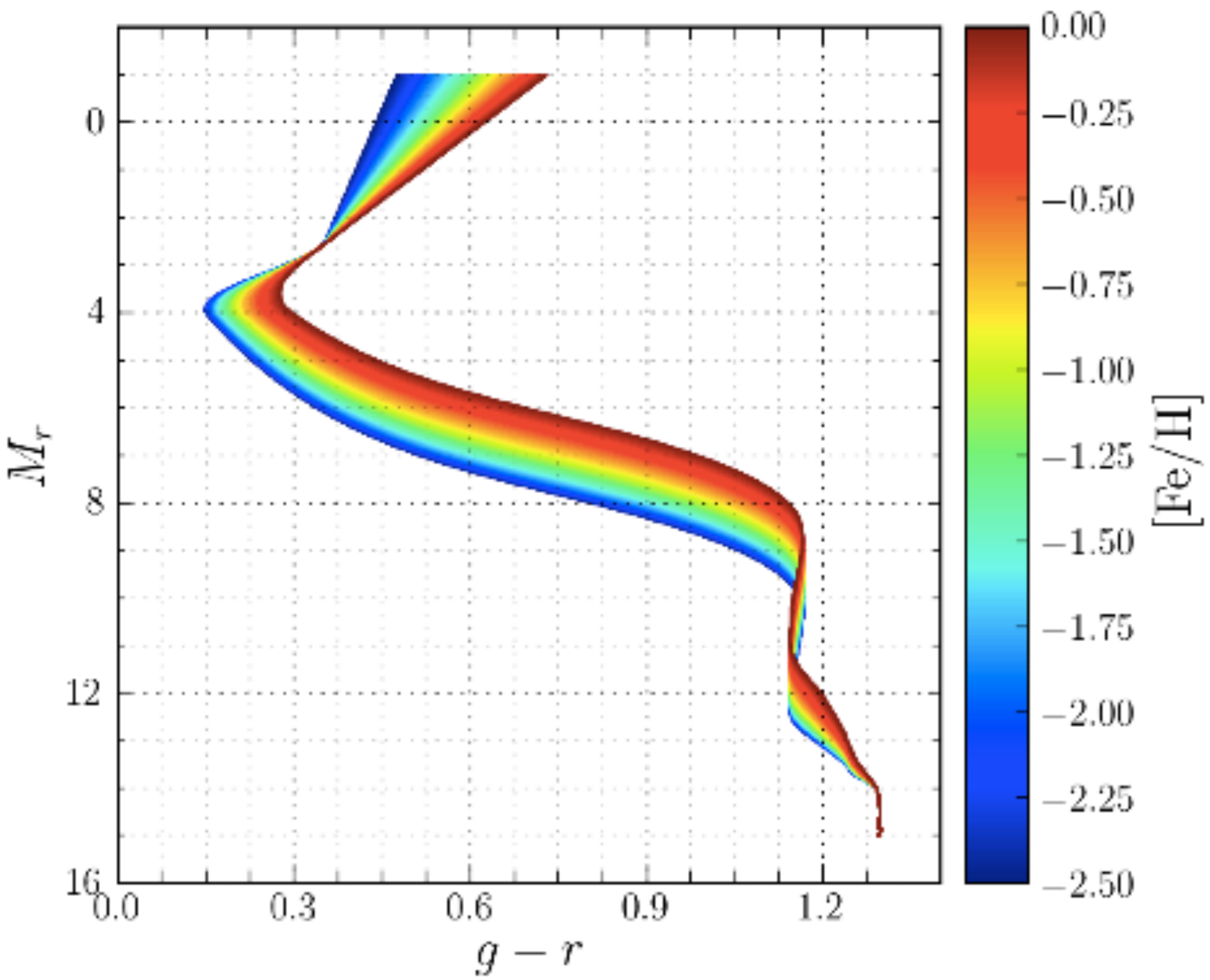
- M_r
- $\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right]$

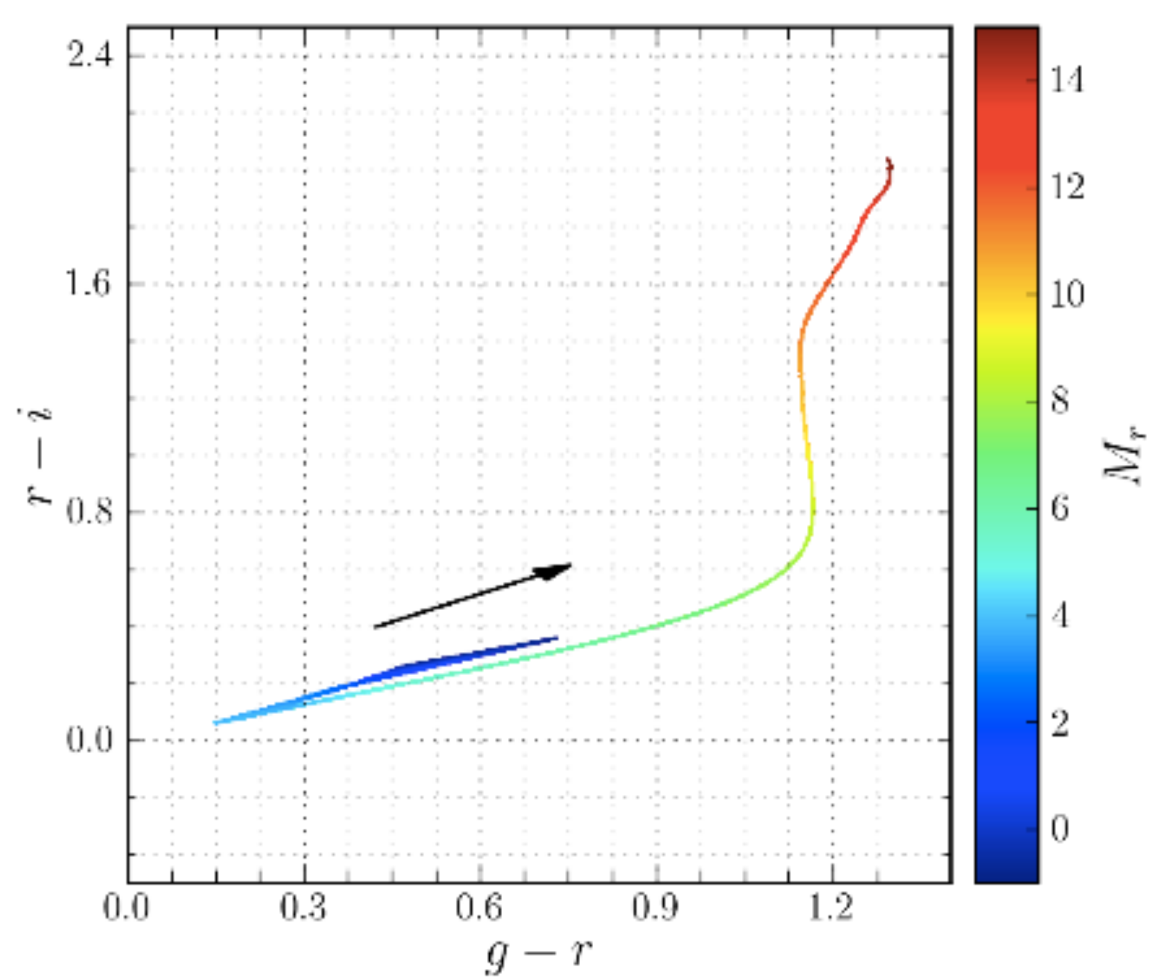
Two extrinsic parameters per star:

- $\mu =$ distance modulus
- $A_r =$ extinction in r-band

3-D dust with Pan-STARRS

- Colors are queried in a stellar template library indexed by M_r and $[{}^{Fe}/_{H}]$.
- $R_V = 3.1$ is assumed, fixing reddening vector.





3-D dust with Pan-STARRS

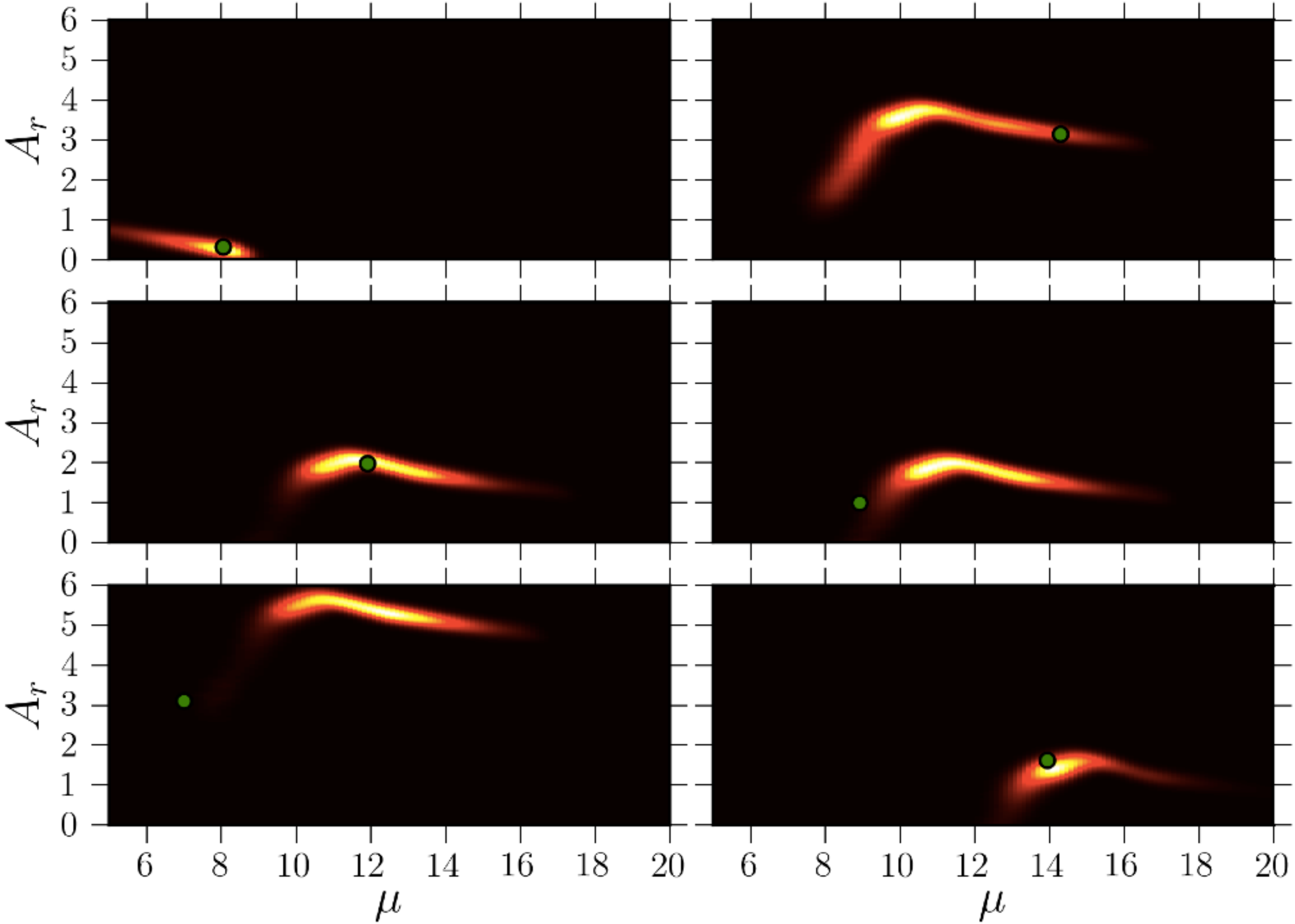
- Given M_r, $[^{Fe}/_{H}]$, μ and A_r, we generate apparent magnitudes:

$$\vec{m} = \vec{M}(M_r,\, [^{\mathrm{Fe}}/_{\mathrm{H}}]) + \vec{A}(A_r) + \mu\,.$$

- We can calculate the likelihood of the observed magnitudes, given a set of model parameters:

$$p\left(\vec{m}_{\mathrm{obs}} \,|\, \mu,\, A_r,\, M_r,\, [^{Fe}/_{H}]\right) = \mathcal{N}\left(\vec{m}_{\mathrm{obs}} - \vec{m},\, \vec{\sigma}\right)\ .$$

- Use Markov-Chain Monte Carlo technique to sample from posterior.
    - Multimodality of posterior.
    - Population-based MCMC – "affine sampler" [Goodman & Weare, 2010].

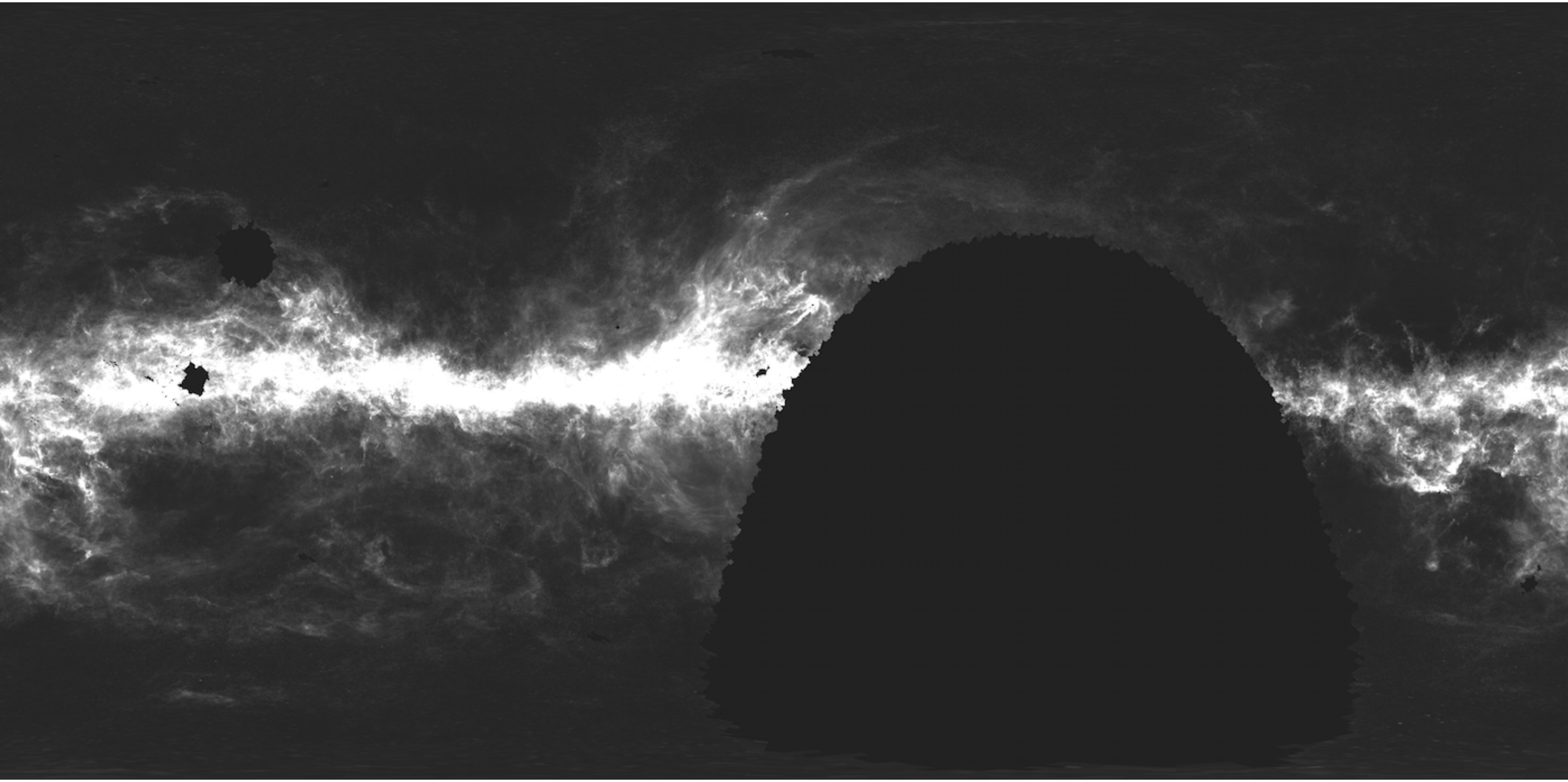


A_r
A_r
A_r
μ
μ

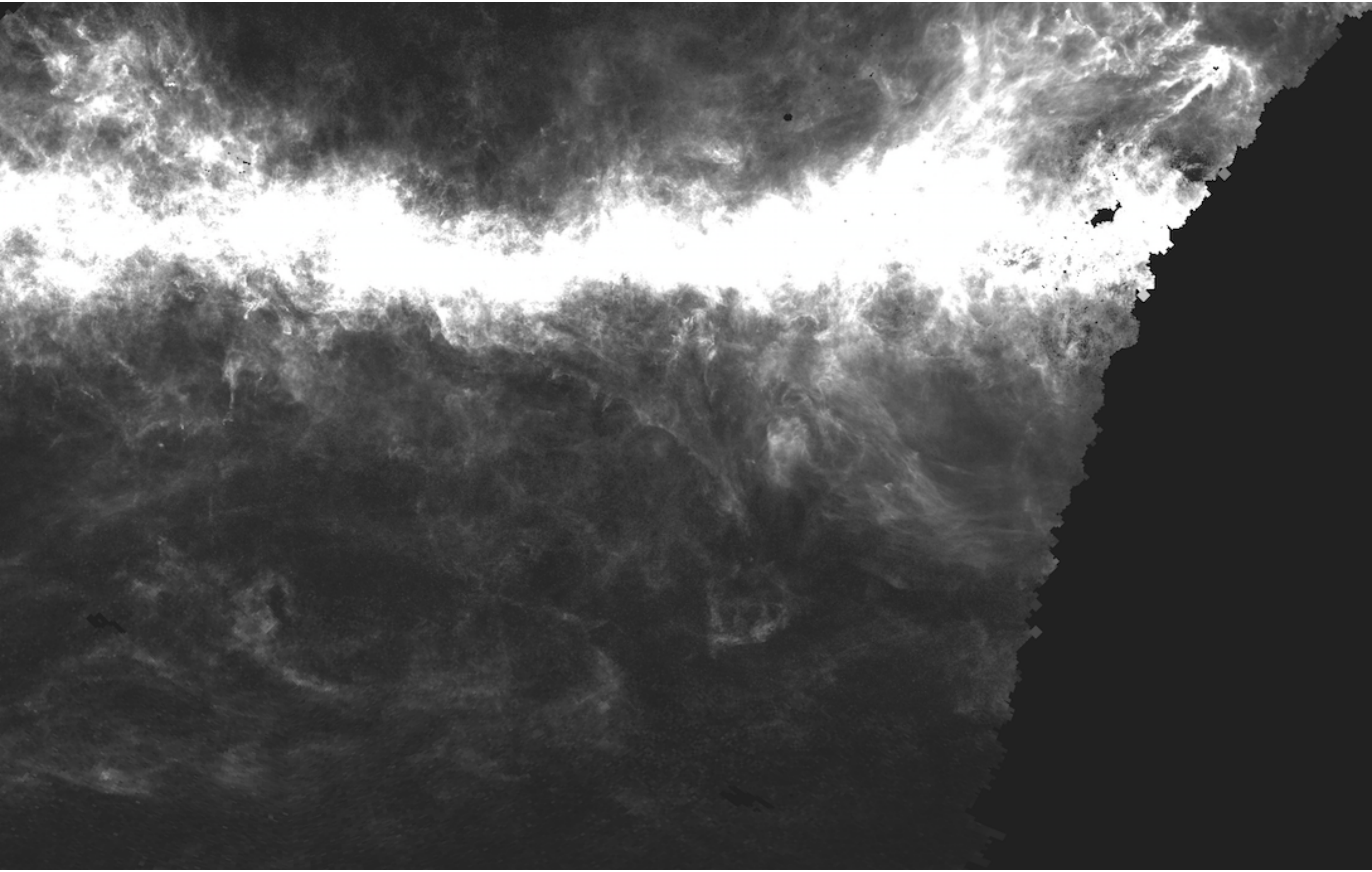
Do this for many stars.

Combine 100-1000 stars per pixel to obtain estimate of dust along each line of sight.

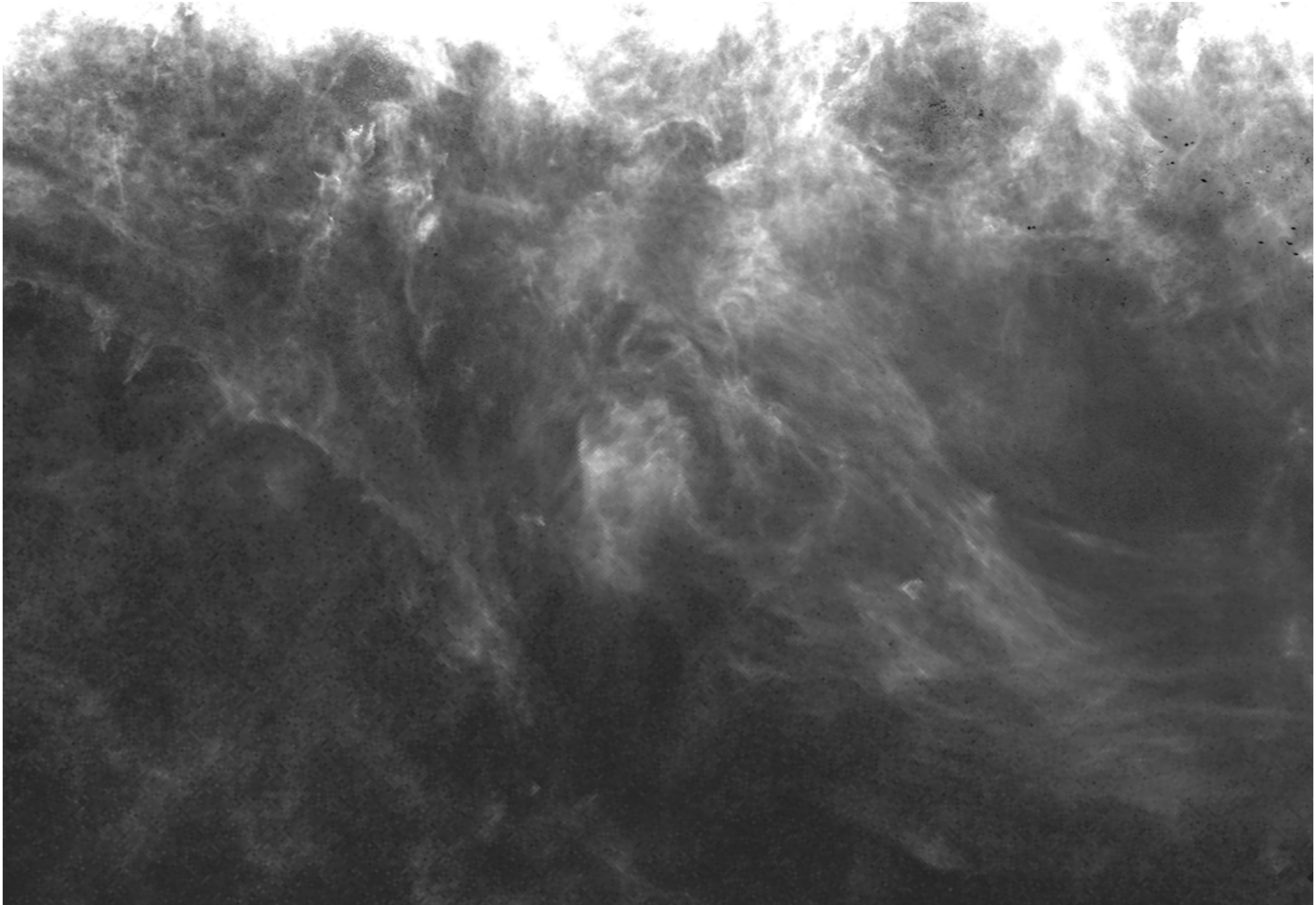
Do this for millions of pixels.



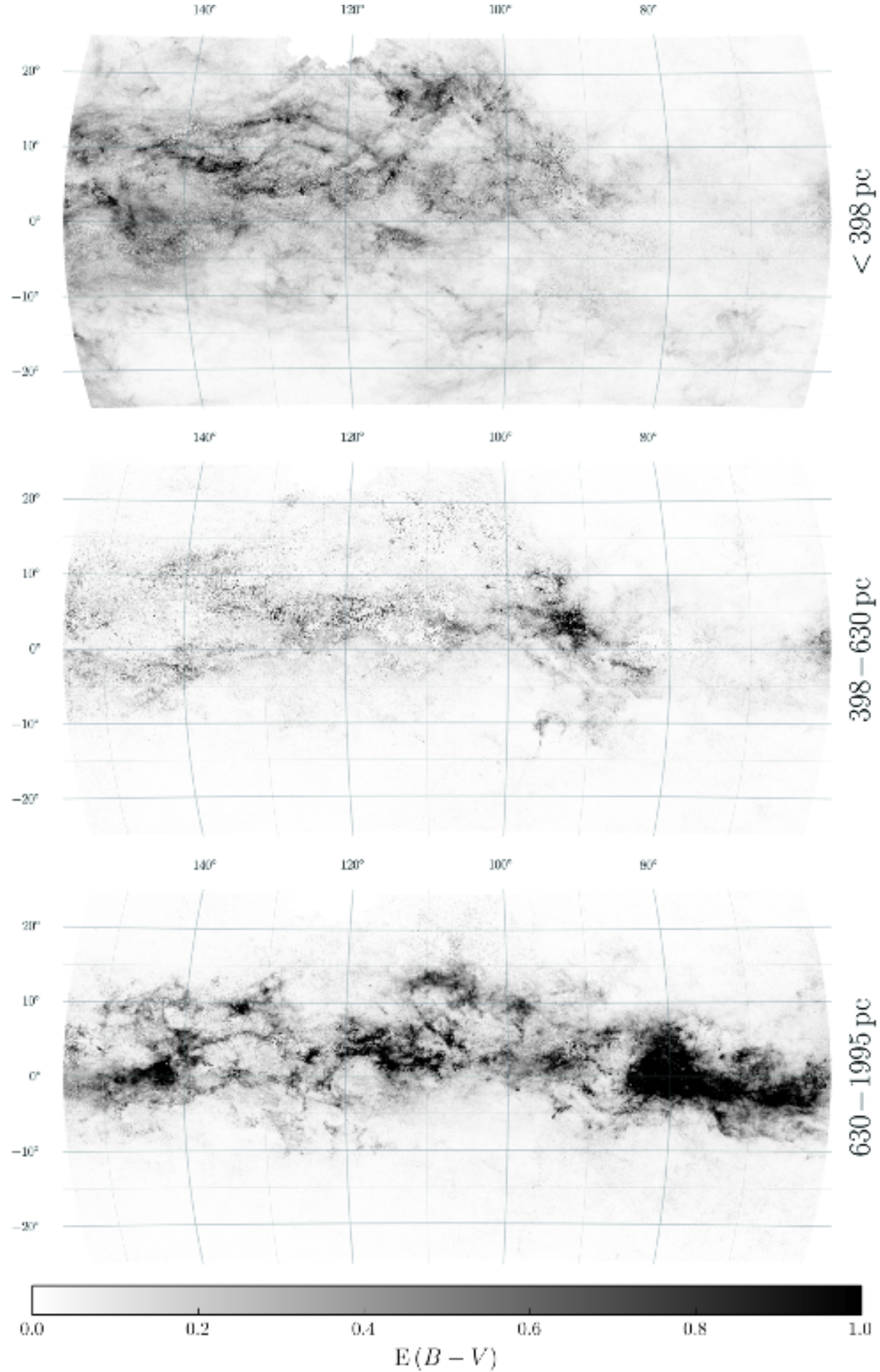
Green+ (2014), Schlafly+ (2014)



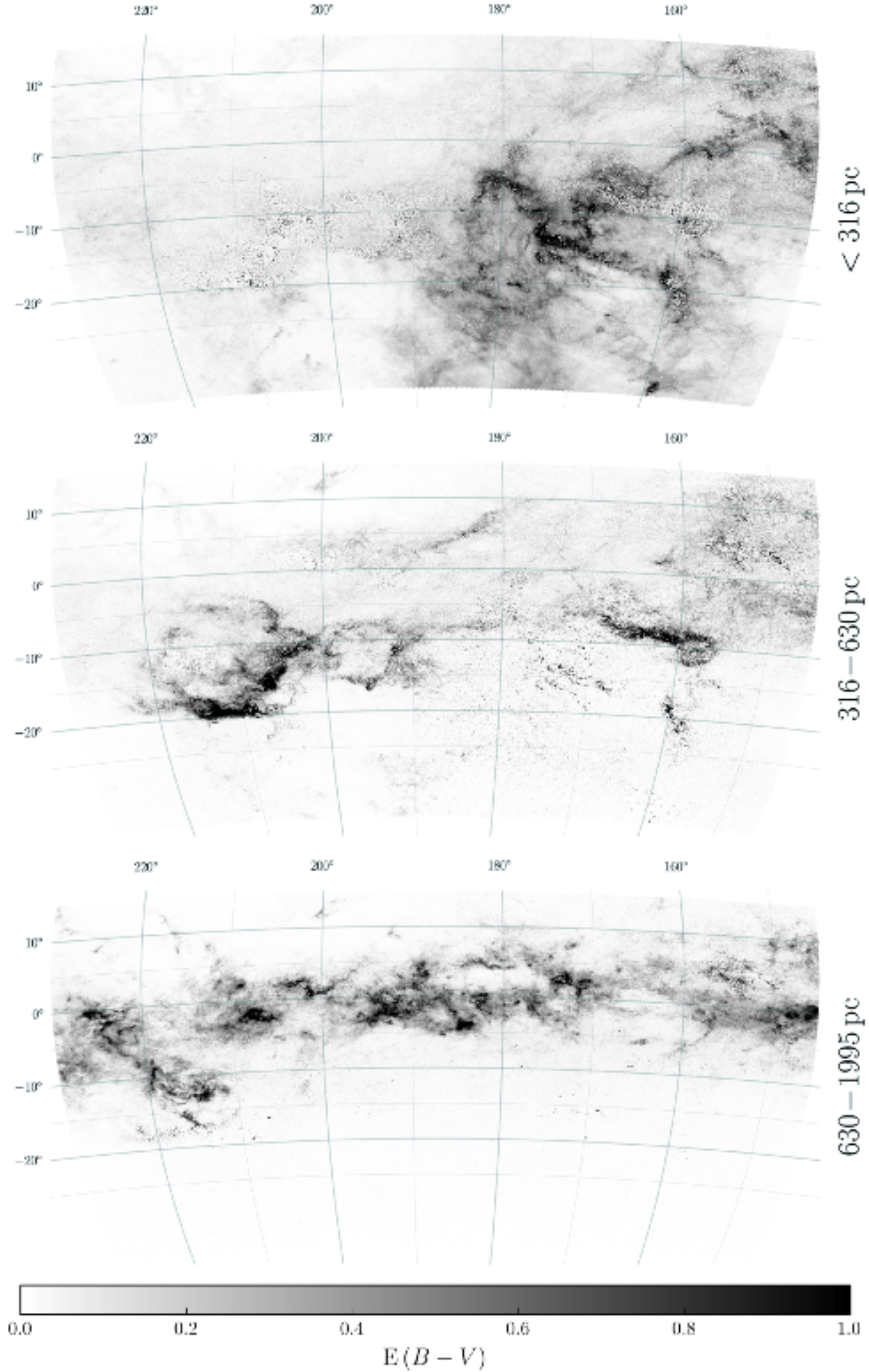
Green+ (2014), Schlafly+ (2014)



Green+ (2014), Schlafly+ (2014)

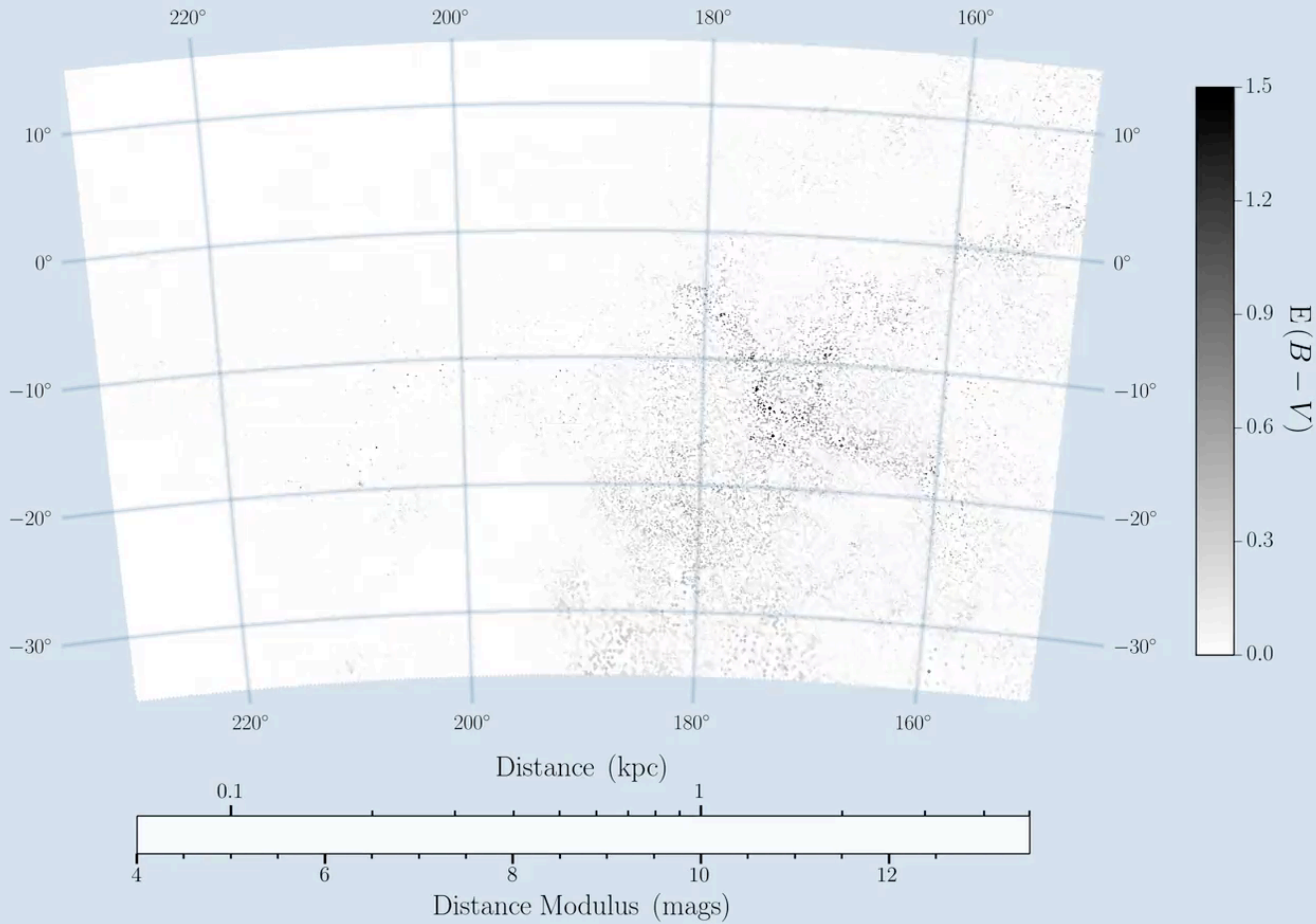

140°
120°
100°
80°
20°
10°
0°
−10°
−20°
< 398 pc
398 − 630 pc
630 − 1995 pc
0.0
0.2
0.4
0.6
0.8
1.0
E(B − V)

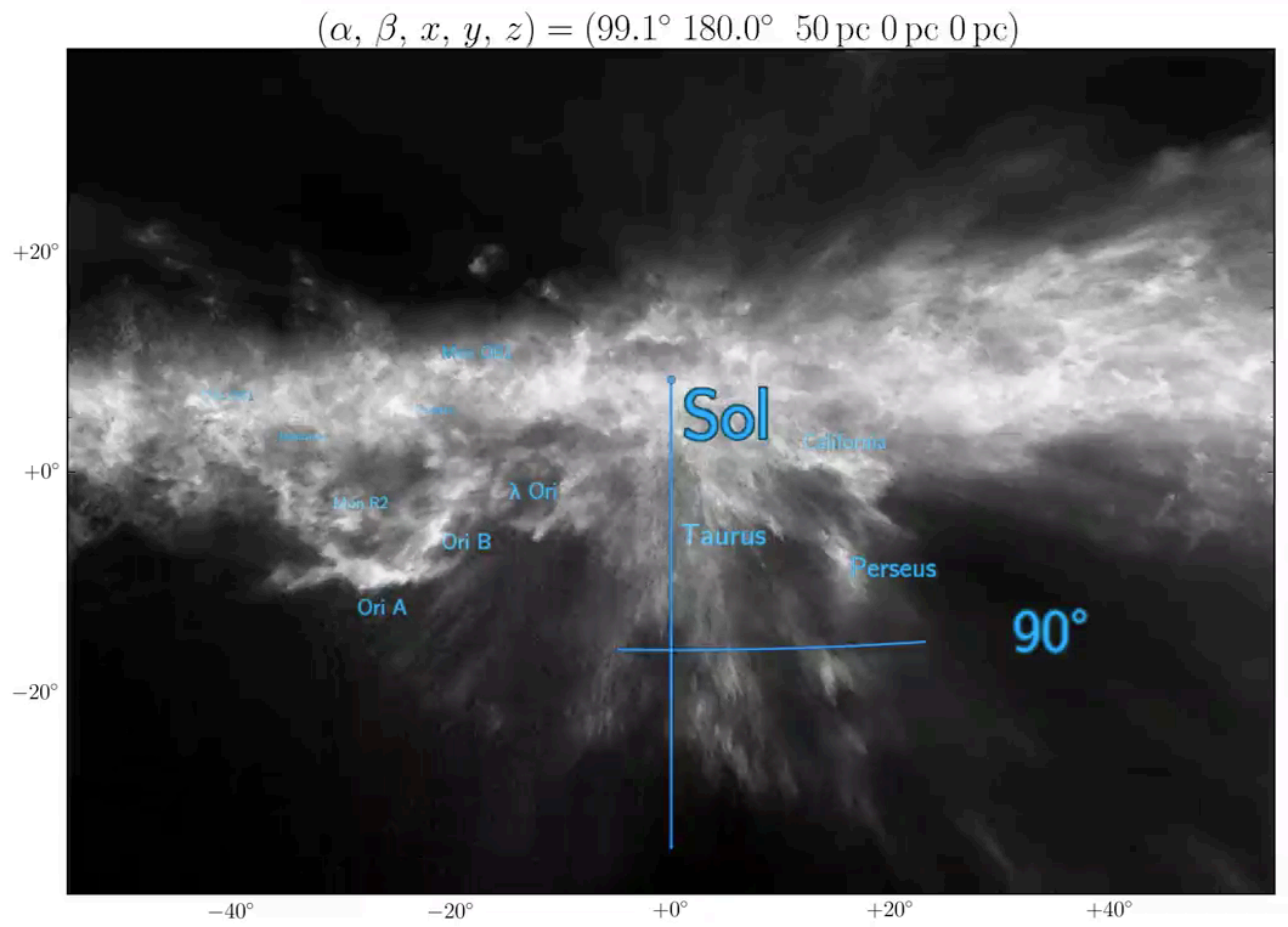
Green+ (2015)



220°
200°
180°
160°
10°
0°
−10°
−20°
< 316 pc
316 − 630 pc
630 − 1995 pc
0.0
0.2
0.4
0.6
0.8
1.0
E (B − V)

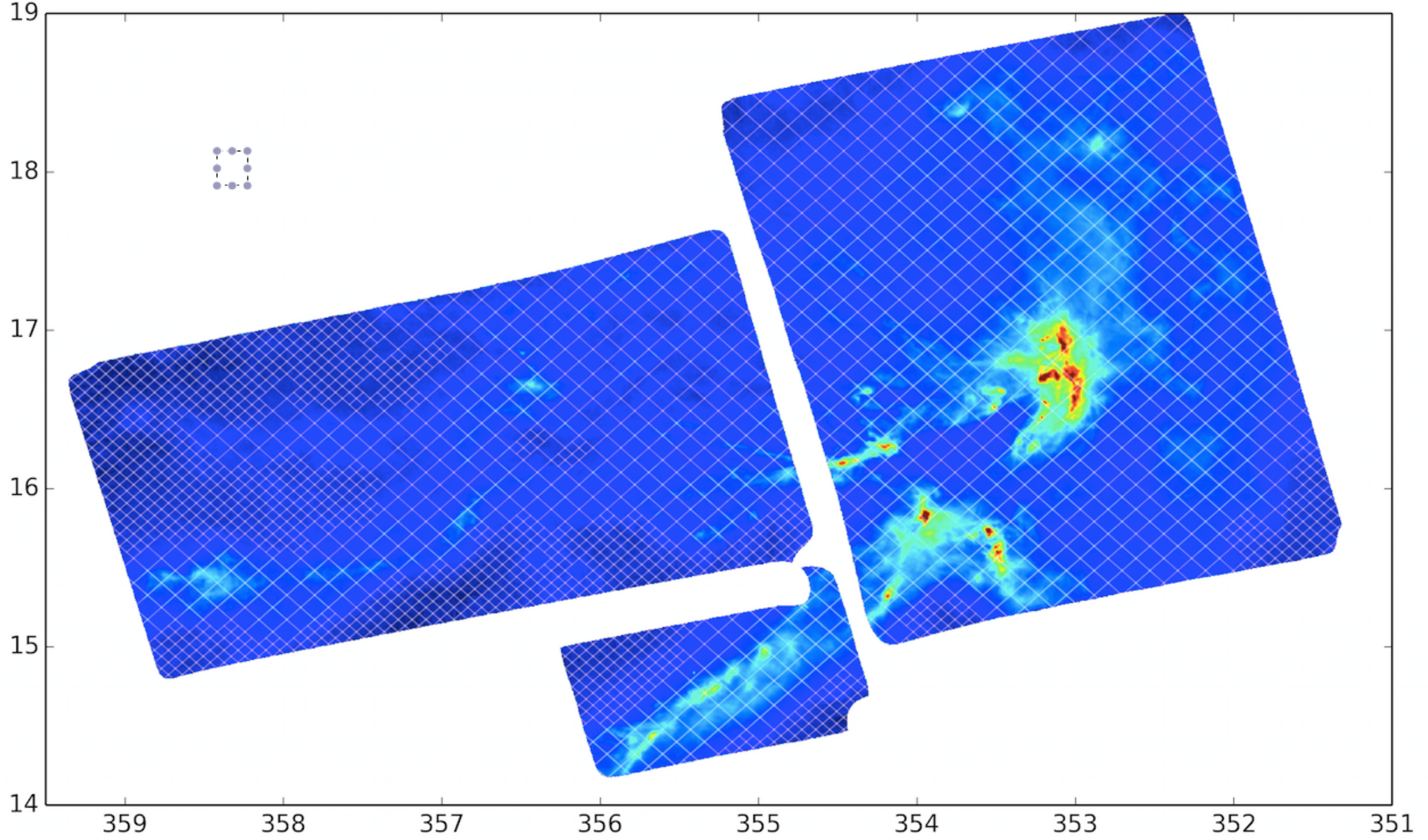
Green+ (2015)


220°
200°
180°
160°
10°
0°
−10°
−20°
−30°
1.5
1.2
0.9
0.6
0.3
0.0
E(B − V)
Distance (kpc)
0.1
1
4
6
8
10
12
Distance Modulus (mags)



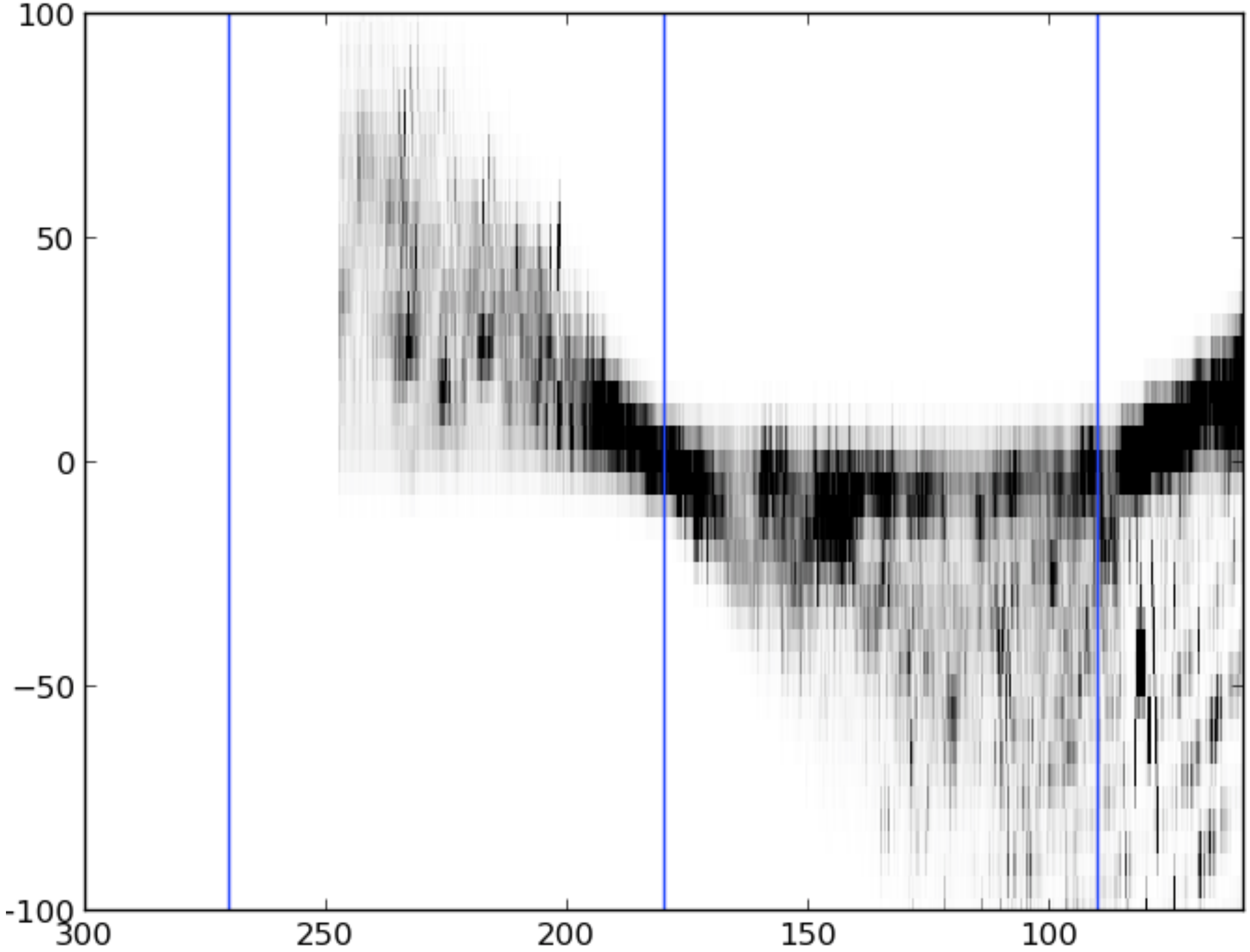
$(\alpha,\ \beta,\ x,\ y,\ z) = (99.1^\circ\ 180.0^\circ\ \ 50\,\mathrm{pc}\ 0\,\mathrm{pc}\ 0\,\mathrm{pc})$
+20°
+0°
−20°
−40°
−20°
+0°
+20°
+40°
Mon OB1
Sol
California
λ Ori
Mon R2
Ori B
Taurus
Perseus
Ori A
90°

Herschel shows finer-scale structure



From G. Green and A. Meisner

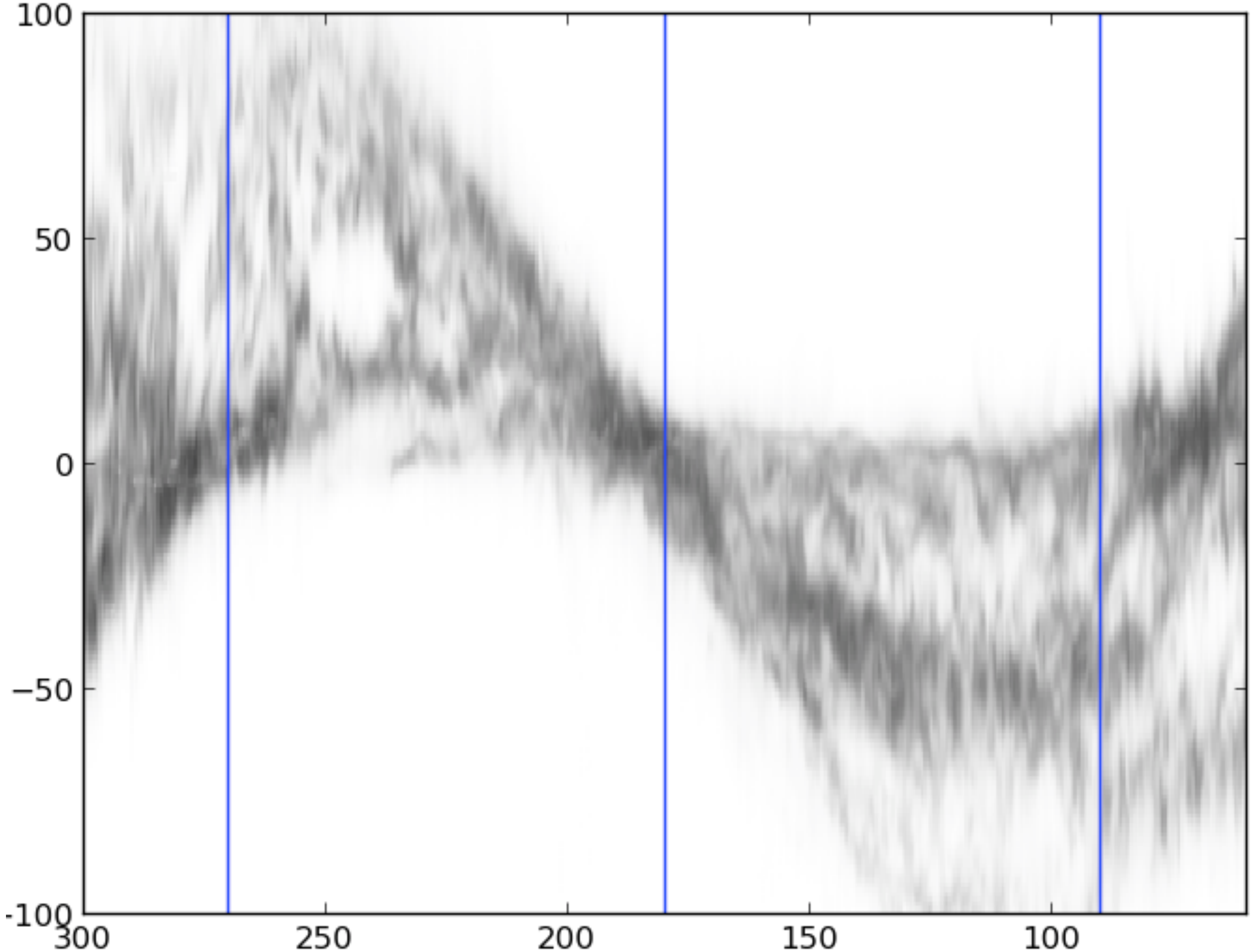
Given rotation curve, map distance to v:



Preliminary!

From E. Schlafly

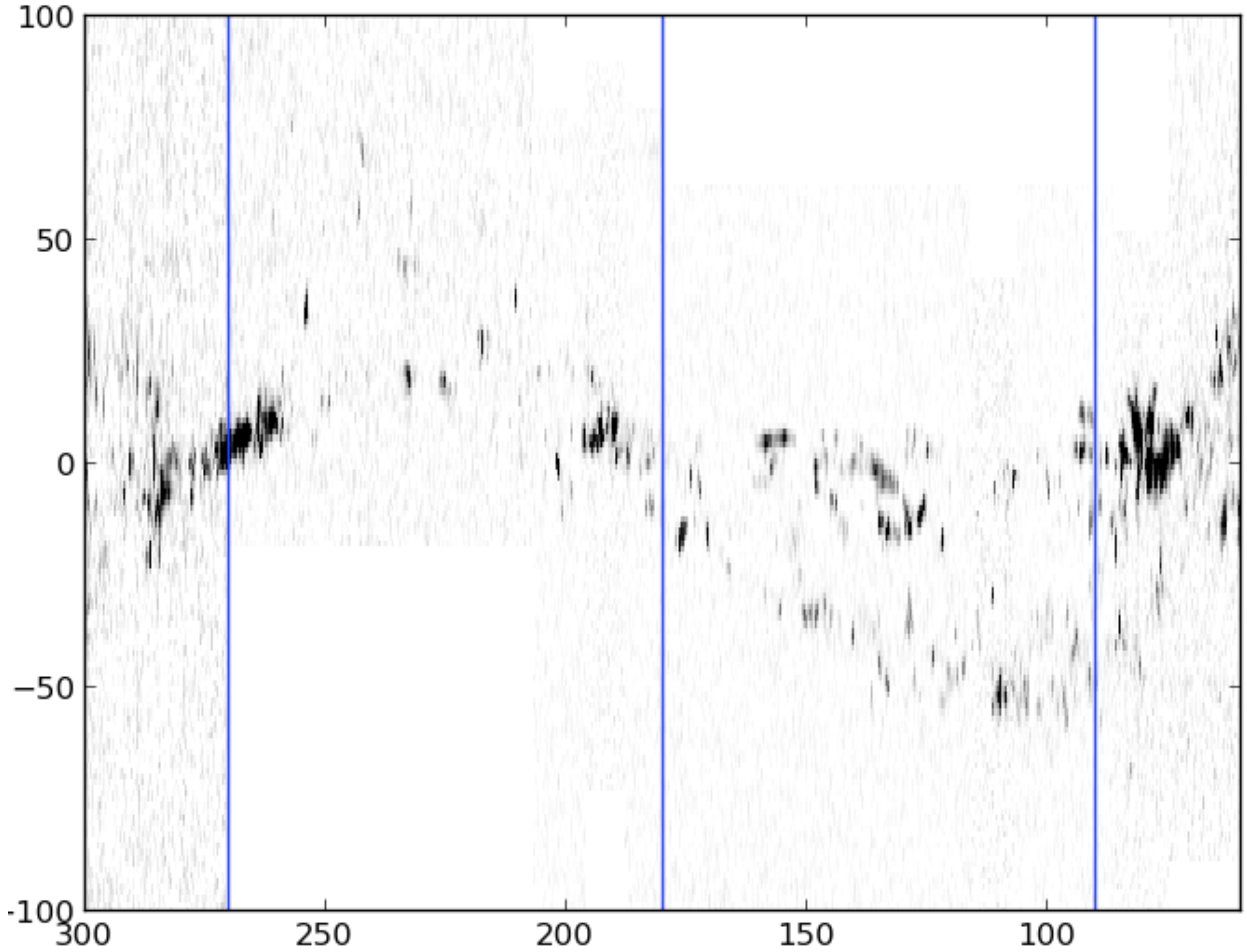
HI



Preliminary!

From E. Schlafly

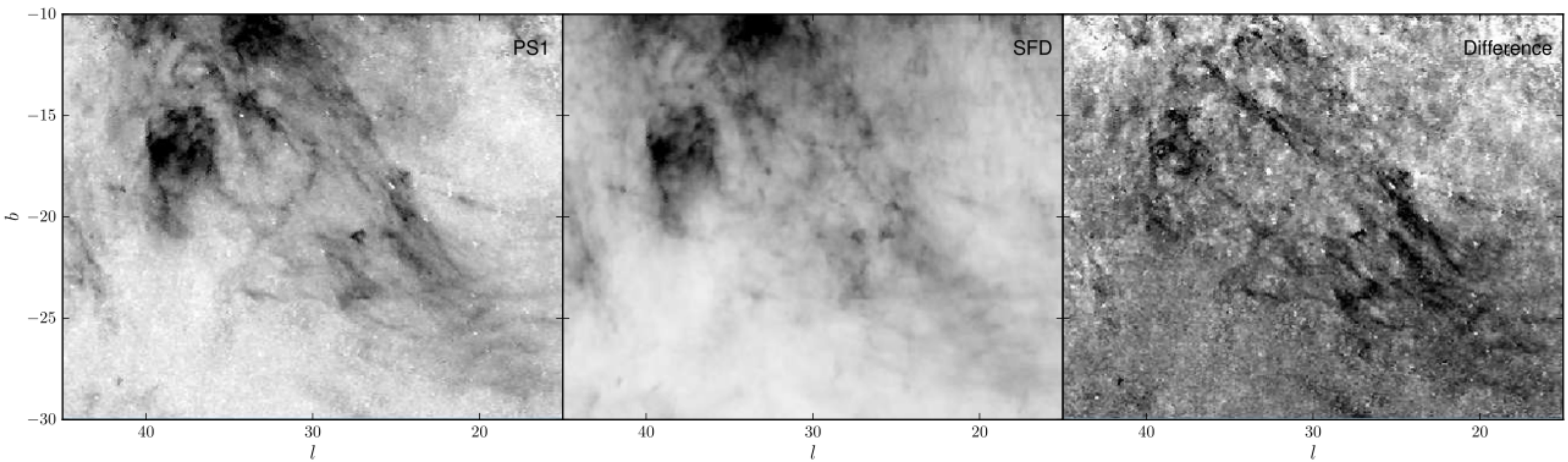
CO



Preliminary!

From E. Schlafly

Comparison to SFD



Comparison to Schlafly+ (2014) 4.5 kpc map

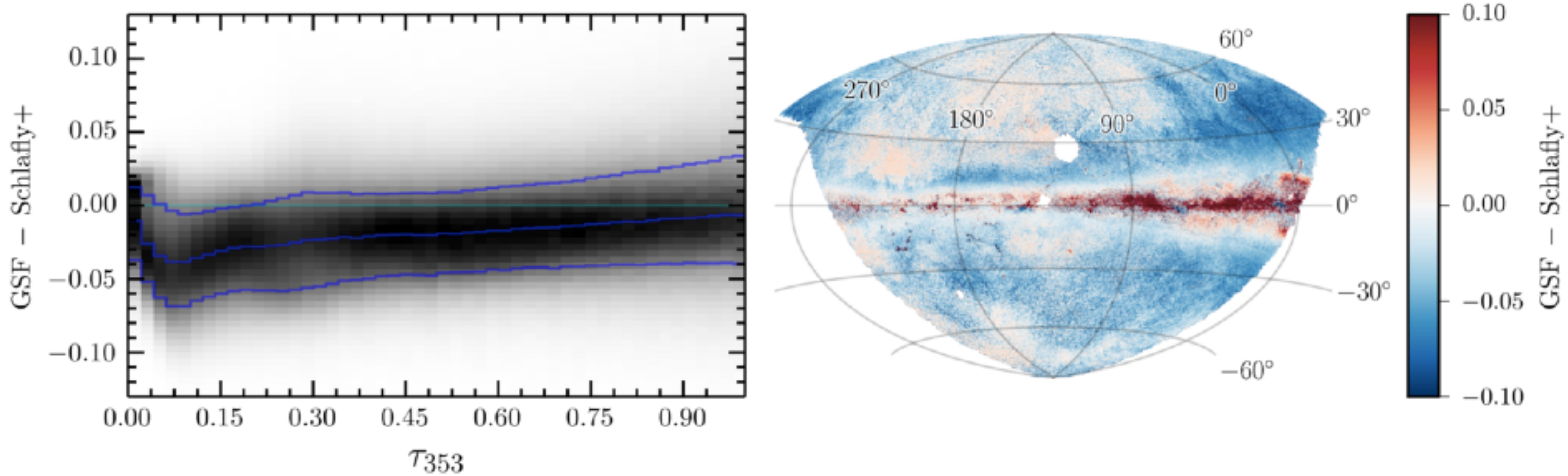


FIG. 10.— A comparison of our new 3D dust map ("GSF"), integrated to 4.5 kpc, with the 2D map presented in Schlafly et al. (2014c). The left panel shows the difference between our map and Schlafly et al. (2014c) as a function of a third reddening measure with uncorrelated errors, the Planck $\tau_{353\,\mathrm{GHz}}$-based dust reddening map. The right panel maps the median residuals between our map and Schlafly et al. (2014c) across the sky. All units are in magnitudes of E($B-V$).

Green+ (2015)

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- What dust is
- What we know about variability in the reddening law
- How APOGEE has helped us find a new parameterization thereof
- How we make emission-based dust maps and estimate their systematics
- How we made the PS1 absorption based map and its issues
- How LSST can help make better dust maps
- How good those maps need to be for LSST science.

There is still much to do

Possibly, stellar reddenings from LSST+ Gaia make a better dust map than anything else in the LSST era.

The 3D aspect is critical for Galactic studies.

The systematics (no zodi, no LSS, no dust/gas ratio variations) are better for cosmological work.

The noise *might* be low enough, and stellar models *might* be good enough.

Reddening law variation is important, but getting nailed down.

I do not know how well we need to do for LSST, or if we can. But LSST data may be the key to making a good-enough map.